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LEVEEMSU: A SOFTWARE PACKAGE DESIGNED FOR LEVEE UNDERSEEPAGE ANALYSIS

by

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This report describes the development, testing, and use of a software package named LEVEEMSU. This software was specifically designed for levee underseepage analyses. As such, it provides certain advantages for such analyses not afforded by either conventional hand analysis or general-purpose seepage analysis programs.

Using the finite-difference method and microcomputer hardware, equations and assumptions used in conventional levee underseepage analysis are extended to levee cross-sections having irregular geometry, variable permeability, and/or variable landside water levels. Thus, the program provides a capability to analyze the effects of ditches, borrow pits, sloping ground, and other irregularities in a manner consistent with current and traditional analysis procedures for uniform cross-sections.

A number of parametric studies and prototype reach analyses are provided to demonstrate the capabilities of the program. Keywords;

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PREFACE

The study reported herein was performed for the US Army Engineer Waterways Experiment Station (WES) under Contract No. DACW39-88-P-1055 with Michigan State University during the period 4 August 1988 through 31 May 1989. Improved methods of underseepage analysis were identified as a research need of the "Rehabilitation Alternative to Control Adverse Effects of Levee Underseepage" work unit of the Repair, Evaluation, Maintenance, and Rehabilitation (REMR) Research Program being conducted at WES.

This report was prepared by Dr. Thomas F. Wolff who was assisted by Mr. Magdal N. Haji.

The work was performed under the direct supervision of Mr. Gerald B. Mitchell, Chief, Soil Mechanics Branch (SMB), Soil and Rock Mechanics Division (S&RMD), Geotechnical Laboratory (GL), WES. Mr. Hugh M. Taylor, Jr., was Principal Investigator and Contracting Officer's Representative, SMB, during the conduct and publication of the work. General supervision was provided by Dr. Don C. Banks, Chief, S&RMD, and Dr. William F. Marcuson III, Chief, GL, WES.

Data and technical support for the study were provided by Messrs. George Mech, Sibte Zaida, and Donald Bawmann of the Rock Island District; Bruce H. Moore, George J. Postol, and Patrick J. Conroy of the St. Louis District; Joseph Keithly and John Monroe of the Memphis District; and Bobby Fleming, Wayne Forrest, and Chuck Mendrop of the Vicksburg District. Partial funding has been provided by REMR and the Rock Island and Vicksburg Districts.

Commander and Director of WES during the preparation and publication of this report was COL Larry B. Fulton, EN. Technical Director was Dr. Robert W. Whalin.

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CONVERSION FACTORS, NON-SI TO SI (METRIC)
UNITS OF MEASUREMENT

Non-SI units of measurement can be converted to SI (metric) units as follows:

Multiply	By	To Obtain
feet	0.3048	metres
inches	2.54	centimeters
gallons (US liquid) per minute	0.000006309	cubic metres per second

LEVEEMSU: A SOFTWARE PACKAGE DESIGNED FOR LEVEE UNDERSEEPAGE ANALYSIS

PART I: INTRODUCTION

Background

1. A Repair, Evaluation, Maintenance, and Rehabilitation (REMR) Levee Underseepage Workshop was held at the US Army Engineer Waterways Experiment Station (WES) on 10 April 1984 to establish research needs related to levee underseepage control. Representatives from the Rock Island, St. Louis, Memphis, and Vicksburg Corps of Engineers Districts attended. One research task identified was comparing predicted levee underseepage conditions to observed performance. This task emerged because of concerns that Corps' procedures and criteria may be overly conservative in many instances, requiring costly control measures where they may not be needed, but may be unconservative in other cases by failing to identify areas where sand boils may occur.

2. In September 1986, a critical review of underseepage analysis procedures was prepared by Wolff (1986). This review noted that Corps' analysis and design procedures required a high level of judgment in formulating the problem for analysis. In particular, actual soil profiles and topography are often quite irregular, but the available procedures required modeling level topography with uniformly thick soil layers. The judgments required for this step alone could result in greatly different analyses by different designers. The study reported herein addressed the development, testing, and use of a new computer program LEVEEMSU for analysis of levee underseepage for cross sections with irregular geometry.

Previous Studies

3. The Corps' procedures are based on closed-form solutions for differential equations of seepage flow presented by Bennett (1946). For conditions of irregular geometry of variable properties, solutions cannot be obtained in closed-form, but can be obtained numerically. In 1987, initial research was conducted at Michigan State University regarding the application of numerical methods to levee underseepage analysis (Wolff 1987). It was shown that

special-purpose computer programs had certain advantages over both traditional underseepage analysis procedures and general-purpose seepage analysis programs. As previously noted, traditional procedures (US Army Engineer Waterways Experiment Station 1956a, 1956b) require that single values be assigned to the variables even though the stratum thicknesses, ground and water elevations, etc., often assume different values at different points in the cross section. General-purpose seepage analysis programs using the finite element method (e.g., Tracy 1973) can model such irregularities; however, they often require a relatively high degree of effort to model a problem and interpret the results, even when pre-processors and post-processors are used.

4. The 1987 research included the development of three FORTRAN codes: LEVEEIRR, to model irregular geometry; LEVEE3L, to model three-layer foundations; and LEVEECOR, to model corners or bends in levee alignment. These were "preliminary" programs developed to demonstrate the feasibility of the numerical approach. These programs were used to analyze actual data at a number of levee reaches and back-calculate field permeability values.

Scope

5. This report documents the development, testing, and use of a new computer program, LEVEEMSU, for analysis of levee underseepage. This program represents a second-generation version of LEVEEIRR described above, and includes a number of enhancements. The program uses numerical methods to analyze underseepage for two-dimensional levee cross-sections having nonuniform geometry and properties. Thicknesses and elevations of soil layers, the ground surface, and ponded water all may vary in the horizontal direction. Top blanket permeabilities may be specified independently for each side of the levee and may be constant or may vary as a function of blanket thickness. Heads and gradients are calculated as a function of horizontal location. The effects of a line of relief wells may be modeled. The program features a graphic display of input and results to aid in checking the input and interpreting the results. The graphic window may be changed by the user to look at various regions of the solution at any desired scale. The program is particularly useful for analyzing and designing ditches, borrow pits, etc.

6. LEVEEMSU provides the user a number of advantages over other methods of analysis. As the analysis of interest always involves a levee and two soil layers, data entry can be made more concise than for a general-purpose finite element program, and the program can be designed compactly to provide rapid solutions on inexpensive hardware with minimal memory. Likewise, output can be arranged to provide results in the most meaningful form (e.g., gradient through the top blanket versus distance).

PART II: PROGRAM DESCRIPTION AND SOLUTION TECHNIQUES

Program Description

7. The computer program LEVEEMSU is an entirely new program based on a previous program named LEVEEIRR (Wolff 1987). LEVEEMSU was developed for analysis of levee underseepage and design of underseepage control measures where it is desired to model cross sections having nonuniform geometry or properties.

8. The program is furnished as a binary executable file, LEVEEMSU.EXE, designed to run on IBM (TM) and compatible personal computers under the MS DOS operating system. A math coprocessor is highly recommended. No computer language or compiler need be installed on the computer. The program was developed using Microsoft QuikBasic (TM) and linked to required library files to produce a single executable file. The QuikBasic language was selected in lieu of the more traditional FORTRAN to maximize the use of color and graphics capabilities of microcomputers yet retain the mathematics of the source code in a form that is reasonably readable to engineer programmers. The program can be run in three graphics modes, EGA color, EGA monochrome, and CGA monochrome, depending on the available graphics card, monitor, and whether a graphics screen copy is desired. In the EGA color mode, the geometry of the substratum, top stratum, water, and piezometric grade line are displayed in color. In the EGA and CGA monochrome mode, these are displayed in high-resolution and medium-resolution monochrome, respectively. In the monochrome modes, the graphic screen can be copied to a graphics printer using a screen dump program such as GRAPHICS.COM for CGA and EPSON.COM for EGA.

9. The program reads input data from a separate data file. The format of the input file is described in Appendix A. The program displays default values for certain variables which affect the time required for solution and solution accuracy. These values can be changed from the keyboard during program execution. Results of the analysis are displayed on the graphic screen; a detailed summary of the results is written to an output file which can be printed during program execution or separately later. Details on running the program are described in Appendix B. An example run is shown in Appendix C. Standard input data files are discussed in Part III and listed in Appendix D.

Appendix E presents a hand calculation. A program listing is shown in Appendix F.

Seepage Under Levees

10. Subsurface conditions beneath levees in alluvial valleys are traditionally modeled as two soil layers, a semipervious top blanket or top stratum of clay, silt, or silty sand overlying a pervious substratum of sand. Flood conditions riverside of the levee result in downward flow of seepage through the riverside top blanket, lateral flow through the pervious substratum, and upward flow through the landside top blanket. Given certain conditions of geometry and soil properties, the upward gradient in the landside top blanket can be excessive, and safety against boiling is of concern. Underseepage analyses are performed to predict the piezometric head along the base of the landside top blanket (or at least at the levee toe) and the gradient through the blanket as functions of riverside and landside water levels. Where calculations indicate, excessive gradients are expected, and control measures are designed. These are typically seepage berms or relief wells. Additionally analyses may be performed to assess the effect of proposed or existing control measures.

11. A solution for the piezometric head beneath a semipervious top blanket adjacent to a dam or levee on a pervious substratum was proposed by Bennett (1946). Bennett assumed perfectly horizontal flow in the pervious substratum and perfectly vertical flow in the top blanket. If the thicknesses and permeabilities of the blanket and the substratum are taken as constants, the piezometric head at the base of the blanket and the upward gradient through the blanket can be directly calculated for a number of various boundary conditions using equations. Solutions have been widely published within the Corps of Engineers (US Army Engineer Waterways Experiment Station 1956a, 1956b; Office, Chief of Engineers 1986a, 1986b) and elsewhere (Turnbull and Mansur 1961). Underseepage analysis by the Corps traditionally has utilized these closed-form solutions.

<u>Analysis of Irregular Geometry</u>

12. If numerical methods are used to solve Bennett's (1946) differential equation, the foundation geometry and properties need not be uniform. Rather, values can be assigned or interpolated at a number of points or nodes (as many as desired), and the differential equation satisfied approximately at each node. Solution techniques have been presented by Wolff (1987) and are extended herein.

13. A unit width of levee is modeled as a two-dimensional cross section. Seepage flow is assumed to be horizontal in the substratum and vertical in the top blanket. A one-dimensional numerical solution is obtained by considering a line of nodes along the interface between the substratum and blanket. The program user describes the foundation geometry using x and y coordinates along a number of vertical sections, in a fashion similar to the data input for slope stability analysis programs. The program generates a set of nodes and associated geometry information based on the user input. Dimensions and properties are assumed to vary linearly between nodes. As the piezometric head in the substratum is implied to be constant along any vertical section, the node actually represents the entire thickness of the substratum.

14. Figure 1 illustrates conditions at a typical node. The node (J) is located at coordinates XX(J) and YY2(J) . In the x direction, the node represents a length of substratum and blanket extending halfway to each adjacent node, XX(J-1) and XX(J+1) . In the y direction, the node is associated with a substratum thickness D(J) - YY2(J) - YY1(J) , a blanket thickness Z(J) - YY3(J) - YY2(J) , and a landside water elevation YYWATER(J) . The piezometric elevation at the node, PIEZEL(J) , is calculated by the program.

15. Flow through the represented element of the foundation is lumped at the node for analysis. Referring to Figure 1, continuity requires that at each node landside of the levee,

$$Q_{in} - Q_{out} + Q_{up} \qquad \text{(eq 1)}$$

where Q_{in} is the flow in the substratum toward the node, Q_{out} is the flow in the substratum beyond the node, and Q_{up} is the flow or seepage through the

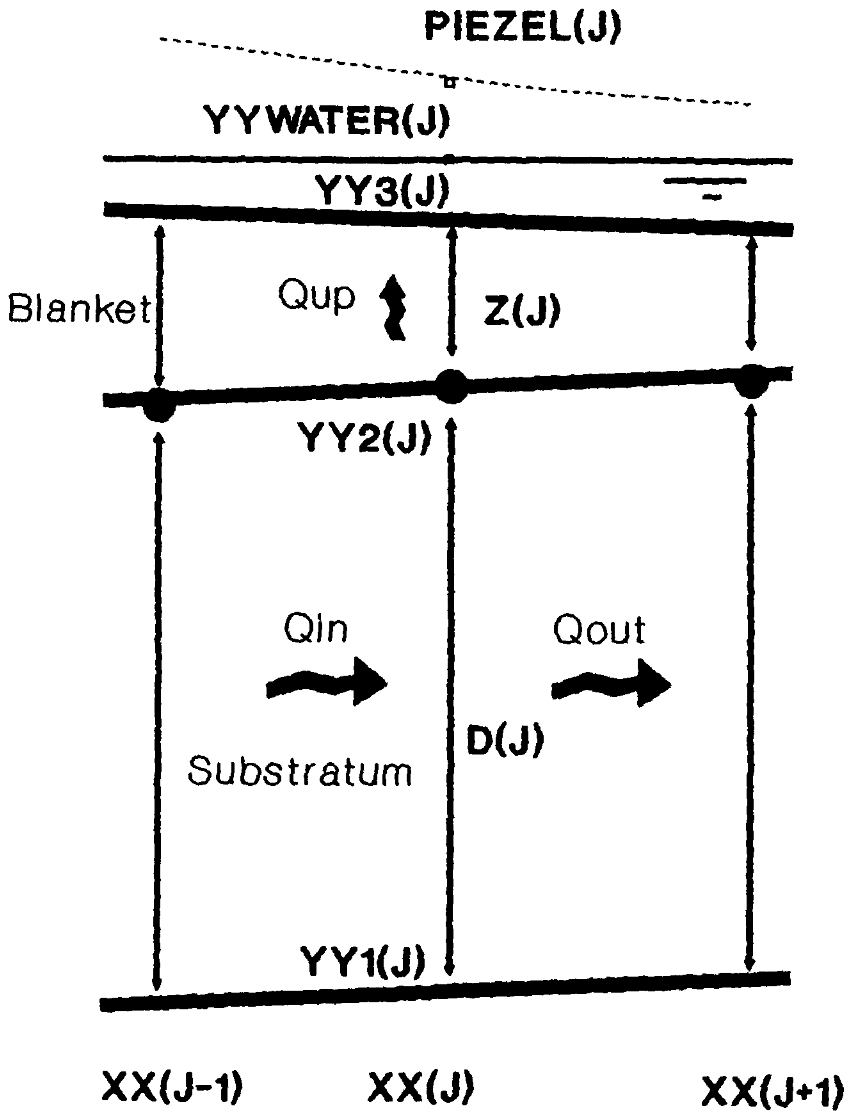

Figure 1. Geometry at a typical node

top blanket in the vicinity of the node. On the riverside of the levee, the same equation is used, but Q_{up} assumes a negative value. Between the landside and riverside levee toes, Q_{up} is taken as zero. From Darcy's law

$$Q = kiA \tag{eq 2}$$

where Q is the flow, i is the hydraulic gradient, and A is the area normal to the flow. The flow terms can be approximated numerically as follows:

$$Q_{in} = (KF) \left|\frac{PIEZEL(J-1)-PIEZEL(J)}{XX(J) - XX(J-1)}\right| \left|\frac{D(J) + D(J-1)}{2}\right| \tag{eq 3}$$

$$Q_{out} = (KF) \left|\frac{PIEZEL(J)-PIEZEL(J+1)}{XX(J+1) - XX(J)}\right| \left|\frac{D(J+1) + D(J)}{2}\right| \tag{eq 4}$$

$$Q_{up} = (KB(J)) \left|\frac{PIEZEL(J)-YYWATER(J)}{Z(J)}\right| \left|\frac{XX(J+1) + XX(J-1)}{2}\right| \tag{eq 5}$$

where

KF is the horizontal permeability of the pervious substratum

KB(J) is the vertical permeability of the blanket at node J

D(J) is the thickness of the pervious substratum at node J

Z(J) is the thickness of the top blanket at node J

XX(J) is the horizontal location of node J

YYWATER(J) is the elevation of ponded water (or ground surface) at node J

PIEZEL(J) is the elevation of the piezometric surface at node J

Substituting the flow Equations (2 through 5) into the continuity Equation 1, the piezometric elevation at any node J , PIEZEL(J) , can be expressed as

$$PIEZEL(J) = \frac{PIEZEL(J-1)*C1(J)+PIEZEL(J+1)*C2(J)+YYWATER(J)*C3(J)}{C1(J) + C2(J) + C3(J)} \tag{eq 6}$$

where

$$C1(J) = \frac{(KF)*(D(J)+D(J-1))}{(XX(J) - XX(J-1))*2} \quad \text{(eq 7)}$$

$$C2(J) = \frac{(KF)*(D(J+1)+D(J))}{(XX(J+1) - XX(J))*2} \quad \text{(eq 8)}$$

$$C3(J) = \frac{(KB)*(XX(J+1)-XX(J-1)}{Z(J)*2} \quad \text{(eq 9)}$$

To obtain a solution, Equation 6 is solved by iteration.

Variable Node Spacing

16. Nodes are generated at the x coordinates specified by the user and at a number of intermediate locations. The locations of all generated nodes are shown on the graphic screen and listed in the output file. The number of nodes used for analysis affects both solution accuracy and solution time. To optimize both of these factors, the node generating algorithm in LEVEEMSU produces nodes at a variable spacing. Near the riverside and landside levee toes, where gradients are the highest and change most rapidly, nodes are generated at a maximum distance of 25 ft apart. The distance between nodes is a default value and can be changed by the user during program execution. At progressively further distances landside and riverside from the levee toes, nodes are spaced increasingly further apart. This technique and the spacing ratios set in the program have been found to provide reasonable, fast, and consistent solutions with relatively few nodes. The algorithm used produces much more consistent results than the scheme used in LEVEEIRR, the predecessor program, which generated a fixed number of nodes between each specified section.

Landside Water Elevation

17. The landside water elevation can be specified independently at any location. Flow is assumed to occur vertically through the top blanket driven by a head equal to the difference of the piezometric elevation at the base of the blanket and the specified landside water elevation. Where landside water elevation is above the ground, consistent values should be specified to model the water surface. Where the landside ground is irregular, specifying the water surface coincident with the ground surface will model water rising to the surface and running off. Where landside swales are separated by relatively high ridges, the user may wish to specify landside water surface elevations lower than the ground surface under the crowns of the ridges. At the user's option, water levels in swales may vary from swale to swale.

Variable Blanket Permeability

18. The in situ vertical permeability of a uniformly thick top blanket during flood may be significantly different on the riverside and landside of a levee. On the riverside, downward flow may enhance siltation, plugging of cracks and defects, etc., reducing the effective permeability. On the landside, upward flow may tend to open defects in the blanket, increasing the permeability. These differences may be modeled with LEVEEMSU by specifying different permeability values for the riverside and landside. When solving Equation 6, the program will check to see whether a node is riverside or landside of the levee and assign the appropriate value for KB .

19. A further refinement allows the permeability to vary inversely as a function of blanket thickness. For levee design along the lower Mississippi River, permeability values are often assigned using curves of permeability versus blanket thickness. This practice reflects the greater probability of blanket defects in thin blankets versus thick blankets. Figure 2 shows the relationship between top blanket thickness and permeability used by the Lower Mississippi Valley Division (LMVD).

20. It is logical to extend this practice to the case of blankets of variable thickness. For this case of a ditch or borrow pit cut partly through a clay top blanket, it is reasonable to expect a higher permeability in the

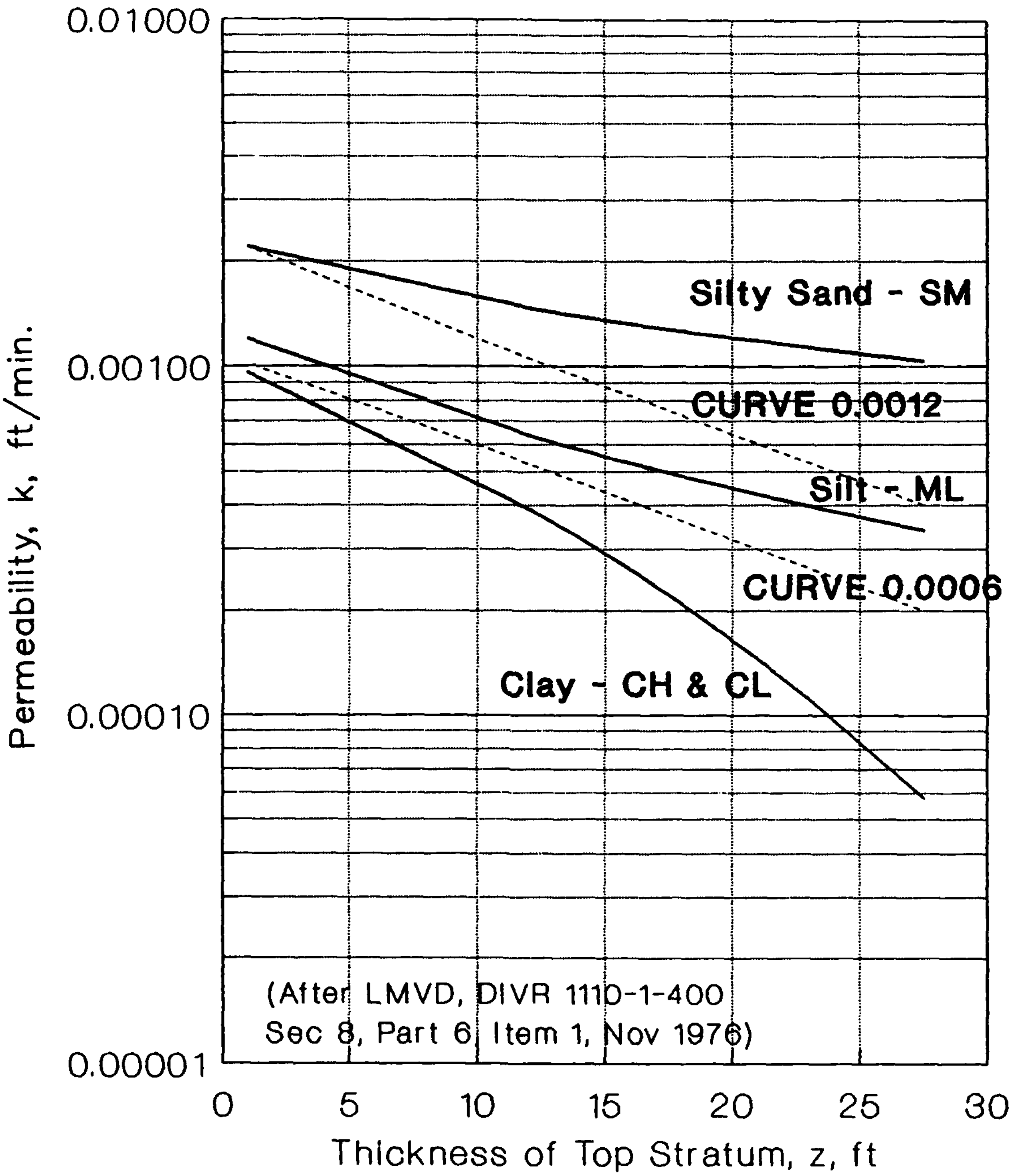

Figure 2. Blanket permeability versus top stratum thickness

ditch bottom or pit bottom than in the thicker adjacent blanket. Rather than program the curves from Figure 2, it was considered more practical to provide the analyst an infinite number of curves. This is done by assuming permeability versus blanket thickness functions that are a family of straight lines on semilog paper approximately parallel to the LMVD curves. These functions are generated by the following equation:

$$KB = \frac{K10}{\exp(-0.065924*(10-Z))} \qquad \text{(eq 10)}$$

where KB is the permeability for a blanket thickness Z and K10 is the permeability of a 10-ft-thick blanket of a given material. The resulting functions are superimposed on Figure 2 for selected values of K10 . When running under this option, the user specified a "curve number" or a value for K10 and the program will calculate the corresponding blanket permeability value at each node.

Modeling a Line of Relief Wells

21. Rigorous analysis and design of relief wells is a three-dimensional, nonlinear problem which is beyond the scope of this report and computer program. However, LEVEEMSU is capable of approximately assessing the effect of a line of relief wells using an option to specify the piezometric elevation at one x coordinate. A specified piezometric elevation can represent the average head in a line of wells (H_{av}) . When this option is used, the variable PIEZEL(J) is forced to the assigned value at the node closest to the specified location and that node is skipped in the iterative solution process. The program will then calculate the flow to the well line required to achieve the specified piezometric elevation as follows:

$$Q_{well} = Q_{in} - Q_{out} - Q_{up} \qquad \text{(eq 11)}$$

This is illustrated in Figure 3. The analyst can then use conventional methods to design a well system that will pass a flow of Q_{well} under the specified head conditions.

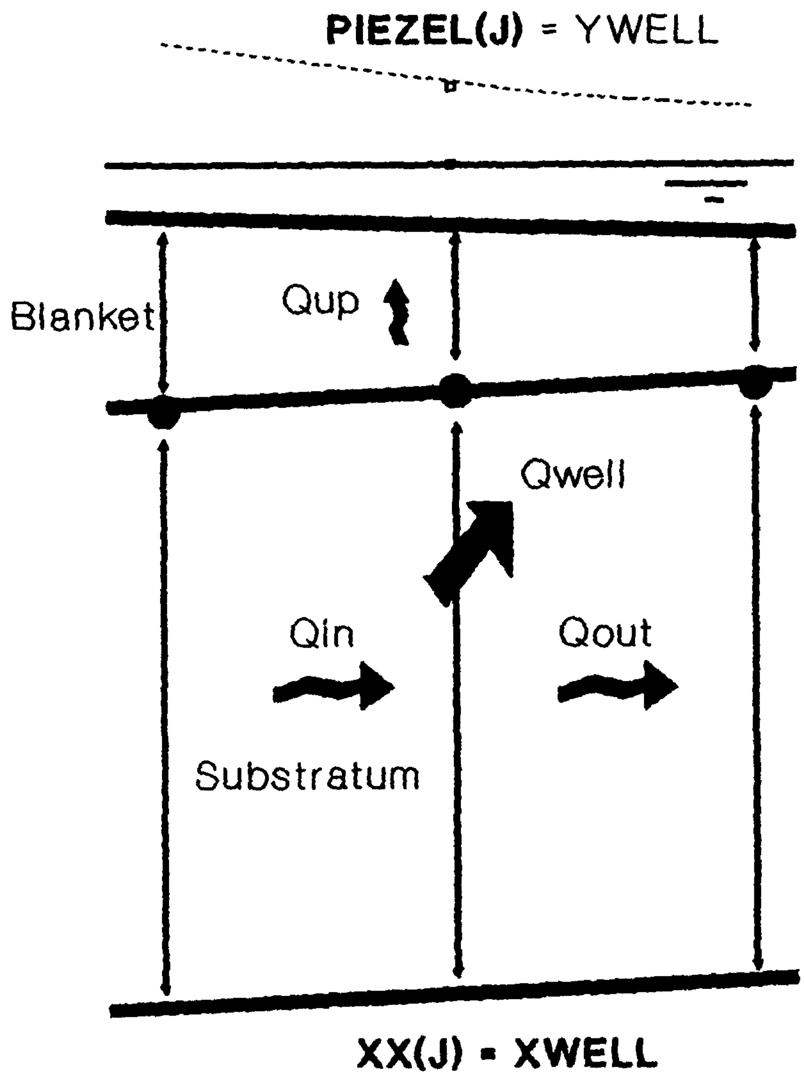

Figure 3. Analysis at a relief well node

PART III: PROGRAM TESTING AND PARAMETRIC STUDIES

Closure Tolerances, Node Spacing, and Number of Iterations

22. The program solves different equations at a finite number of points to approximate the solution of a differential equation over a continuous domain. No exact solution is obtained; rather, continued iterations produce successively more accurate solutions. The iteration procedure is stopped when the maximum residual (change in calculated piezometric elevation at any node between successive iterations) is less than a specified closure tolerance. The program incorporates default values for the closure tolerance, node spacing near the levee, and maximum number of iterations. These can be changed at the user's option during program execution. The closure tolerance must be significantly less than the desired accuracy of the solution, as small changes from one iteration to the next may accumulate toward the "exact" solution. Smaller node spacings and closure tolerances yield more accurate solutions but require longer times to run.

23. A standard input file named DATACHK (listed in Appendix D) was used to initially check program solutions and evaluate relationships among tolerance, node spacing, and number of iterations. This input file models a levee with a uniform substratum and top blanket, $D = 80$ ft and $Z = 10$ ft ; foundation lengths L_1* = 1,500 ft , $L_2 = 300$ ft , $L_3 = 3{,}200$ ft ; and a permeability ratio $k_f/k_b = 1{,}000$. The final screen output for a run using DATACHK and default options is shown in Figure 4. As shown, the program calculates a maximum residual head of 8.87 ft and a maximum gradient of 0.89, both occurring at the landside toe ($x = 1{,}800$ ft).

24. The sensitivity of the results to node spacing and tolerance was examined by systematically adjusting these values during program execution and noting changes in calculated maximum gradient and number of iterations required for solution. Results are shown in Figures 5 and 6. Also shown in Figure 5 is the theoretical maximum gradient of 0.88 obtained from a hand

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* For convenience, symbols and abbreviations are listed in the Notation (Appendix G).

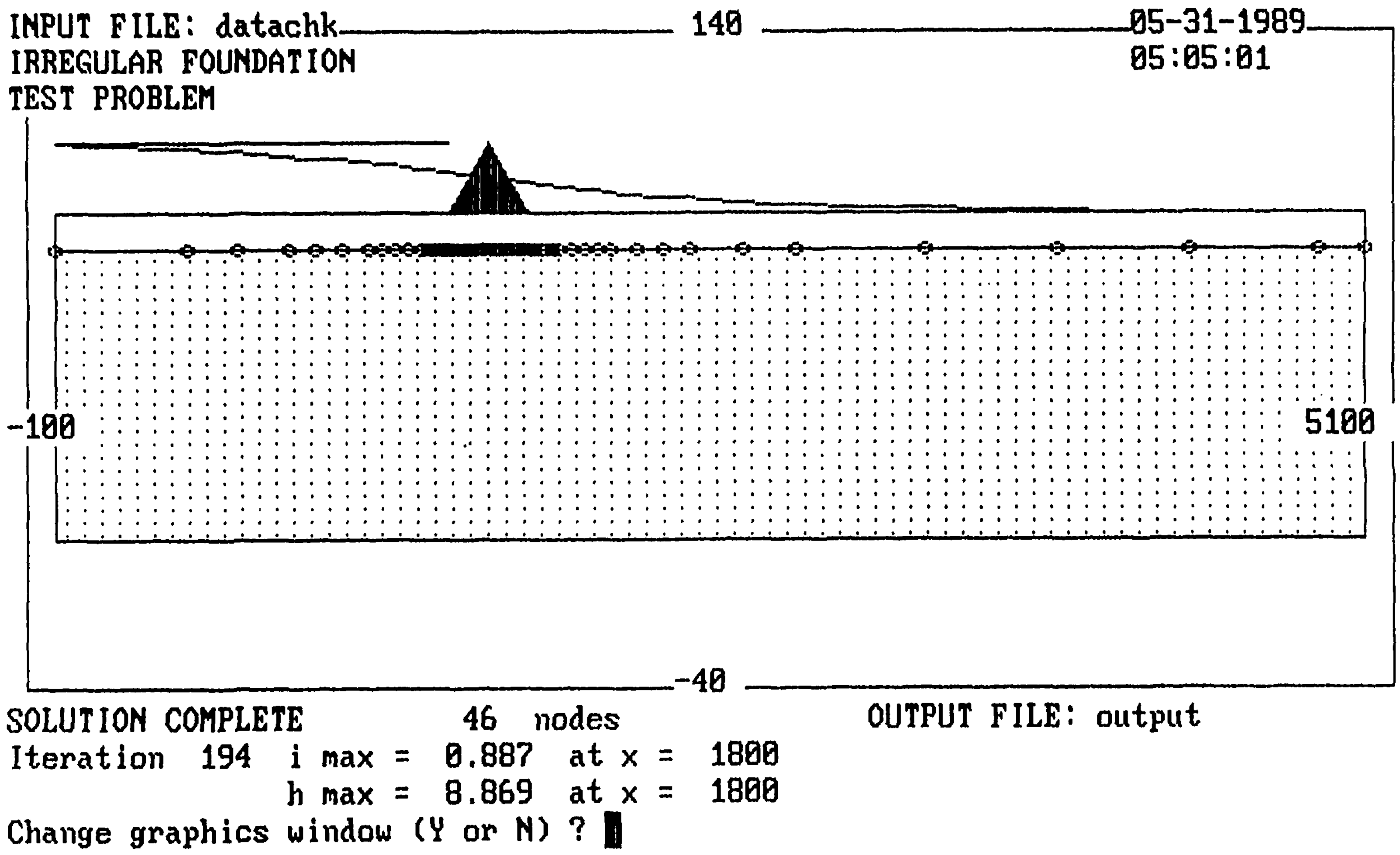


Figure 4. Copy of screen output, file DATACHK

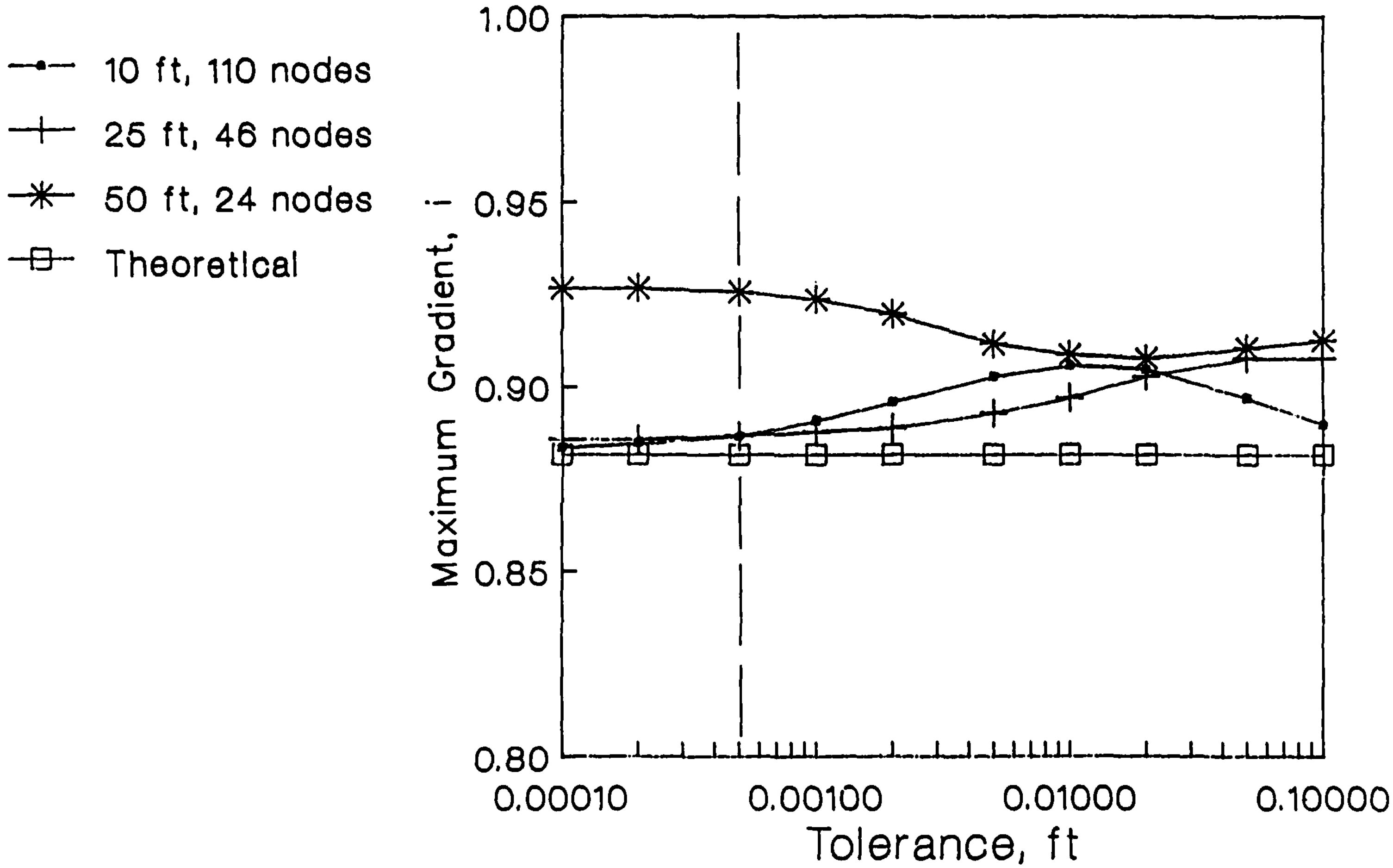


Figure 5. Maximum gradient versus tolerance, file DATACHK

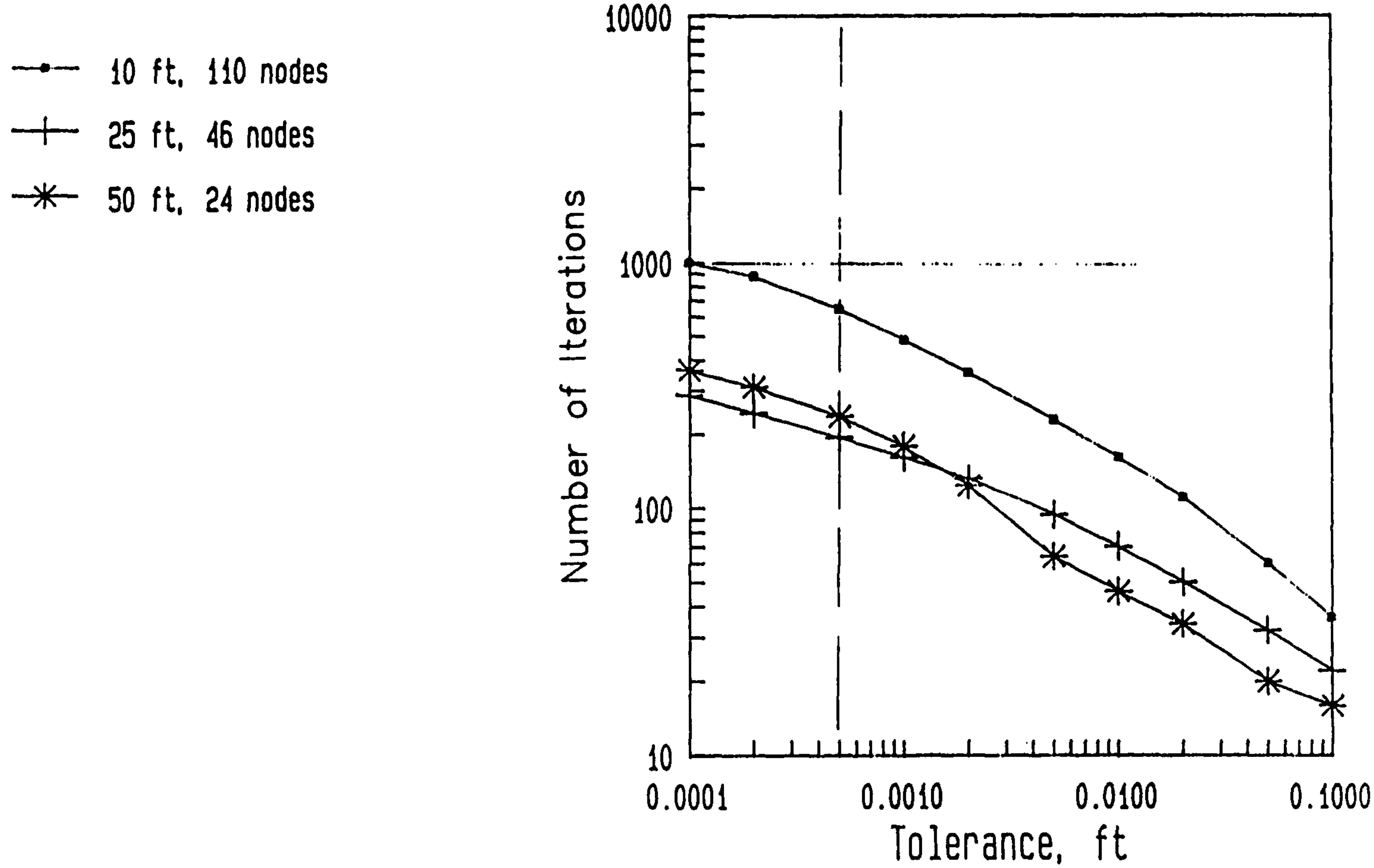


Figure 6. Number of iterations versus tolerance, file DATACHK

check (Appendix E). In Figure 5, it is seen that a node spacing of 25 ft or less and a tolerance of 0.0005 ft are sufficient to calculate a gradient within a few hundredths of the theoretical value. A node spacing of 50 ft was too coarse to accurately calculate the gradient due to the averaging of upward flow conditions near the toe over too large a horizontal distance. Figure 6 illustrates the number of iterations required to converge within the specified tolerance. Decreasing the minimum node spacing to 10 ft increases the number of nodes from 46 to 110, and increases the number of iterations from a few hundred to a few thousand. This produces a negligible increase in accuracy (Figure 5) but a relatively large increase in solution time.

25. The analyses just described were repeated for a levee cross section with irregular geometry using a standard data file names DATAIRR (listed in Appendix D). The screen output from DATAIRR using default parameters is shown in Figure 7; the calculated maximum gradient is 0.41. In this figure, the levee geometry display has been windowed" to eliminate some of the pervious substratum and focus on the area near the levee. As evident from the figure, this file models a top blanket having a thick clay plug parallelling the landside toe, and a broad, water-filled swale on the landside. Because of these irregularities, no closed form solution can be obtained for this problem. Results of the parametric study are shown in Figures 8 and 9. It is seen from Figure 8 that node spacings of 10, 25, and 50 ft all eventually approach a gradient of 0.41 as the specified tolerance is reduced; however, the 10 ft spacing requires reducing the tolerance to 0.0001 ft to achieve convergence. A solution of this problem had previously been obtained (Wolff 1987) using the predecessor program LEVEEIRR. The earlier solution yielded a gradient of 0.37; however, LEVEEIRR was much more sensitive to the way nodes were specified and did not ensure close node spacing near the levee toe. The LEVEEMSU solution is considered to be an accurate solution. It is seen from Figure 9 that the problem DATAIRR required considerably more iterations to reach a solution than did DATACHK, apparently due to the irregular geometry. The program default of 1,000 iterations would still be sufficient to achieve convergence with the default tolerance of 0.0005 ft and default spacing of 25 ft; however, the 10 ft node spacing discussed above required over 4,000 iterations.

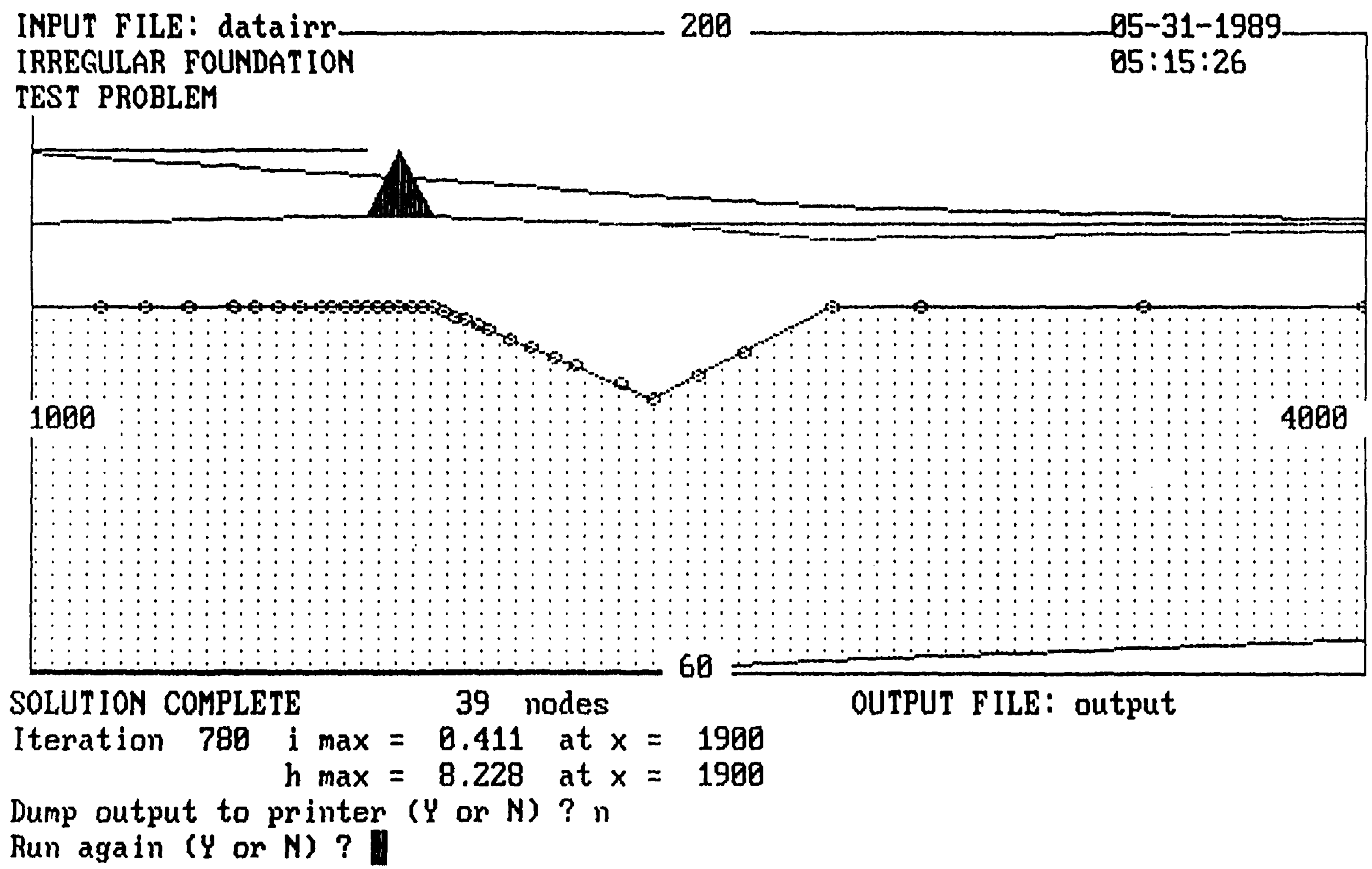


Figure 7. Copy of screen output, file DATAIRR

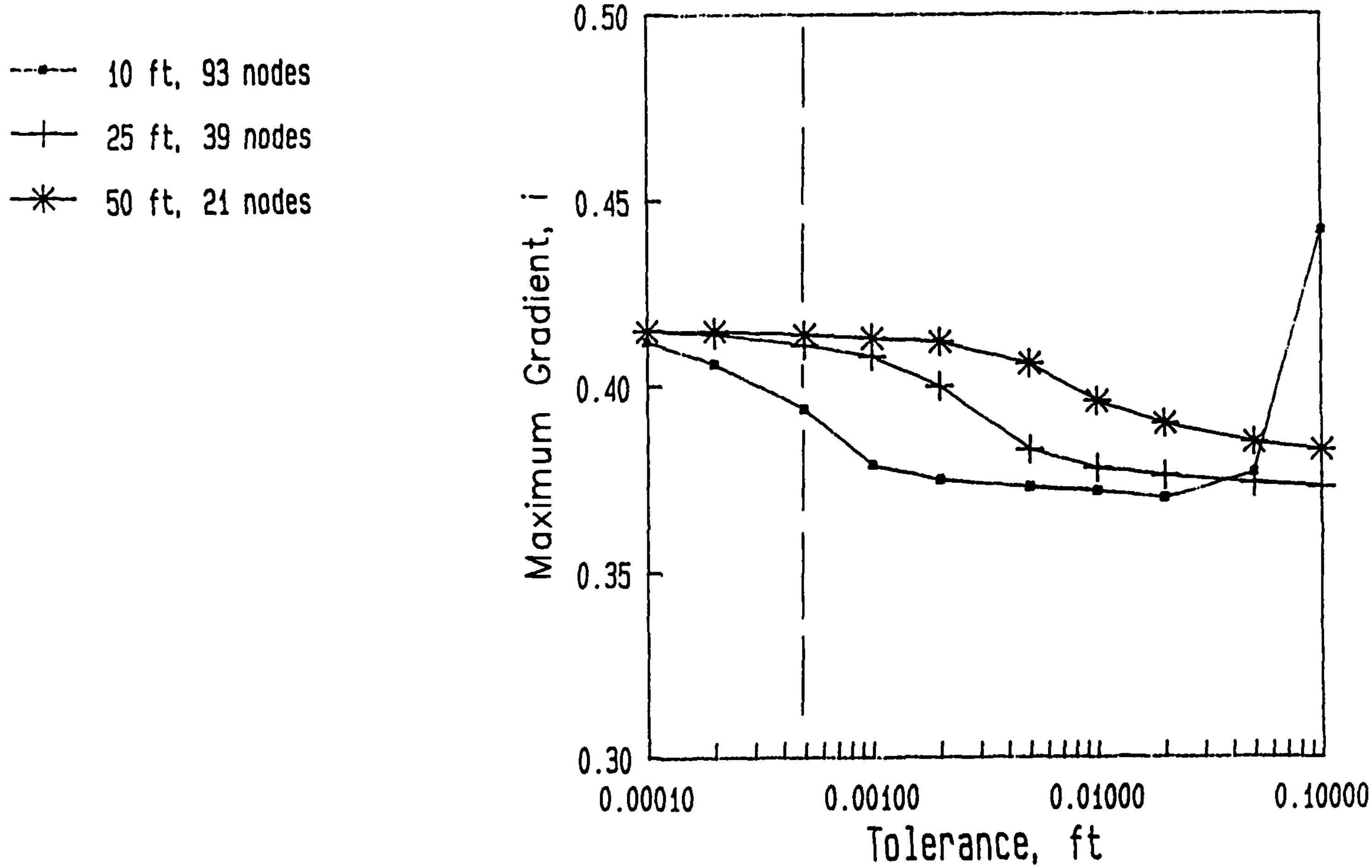


Figure 8. Maximum gradient versus tolerance, file DATAIRR

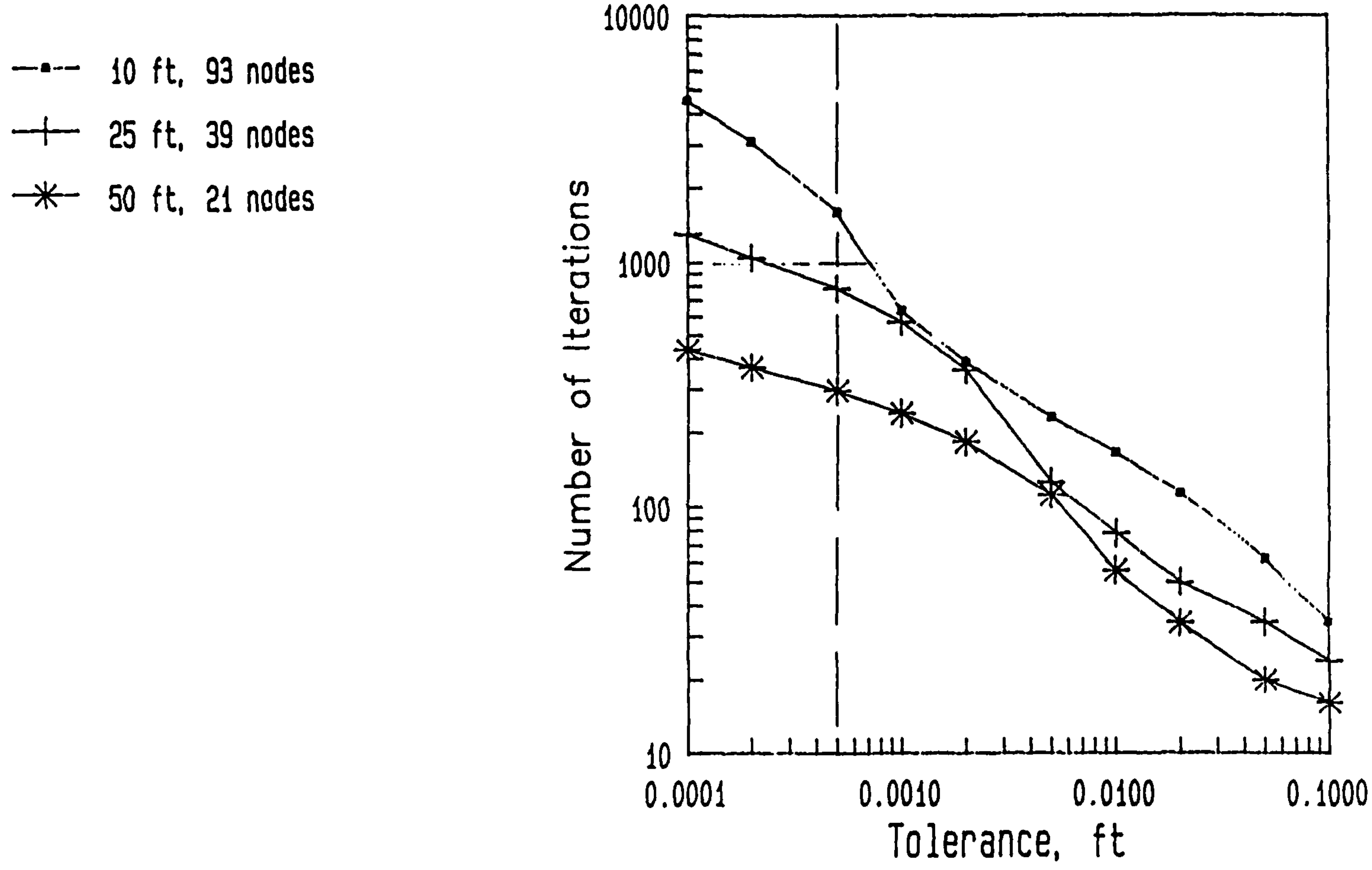


Figure 9. Number of iterations versus tolerance, file DATAIRR

26. Based on the above analyses, program default parameters were set at a node spacing of 25 ft, a tolerance of 0.0005 ft, and a maximum number of iterations of 1,000. These may be changed by the user during program execution. Finer node spacings or finer tolerances will increase the number of iterations; the user is cautioned to ensure the program performs sufficient iterations to reach the desired solution.

Comparison to Manual Solution

27. The program's accuracy was checked by performing a manual analysis for the conditions modeled by the input file DATACHK (Appendix C) previously described. The program output is shown in Appendix C and the manual analysis is shown in Appendix E. The program assumes an open seepage exit at the last specified section, 3,000 ft landward of the levee toe. In the manual analysis, L_3 distances of both 3,000 ft and infinity were checked. The computer solution and manual solutions are compared in Figure 10, which plots the residual head as a function of the distance from the landside levee toe for all three solutions. It is seen that the computer solution is accurate and that an L_3 distance of 3,000 ft accurately models an infinitely long exit condition for this case.

Modeling of Finite and Infinite Geometry

28. LEVEEMSU always models open entrance and exit conditions at the first and last specified vertical sections. Infinitely long entrance (L_1) or exit (L_3) distances must be approximated by specifying the beginning or ending sections at very large distances from the levee. To investigate how great such distances should be, a set of parametric studies was performed by systematically altering the file DATACHK to model different exit lengths, L_3. Results are shown in Figure 11, in which the gradient at the landside toe is plotted versus L_3. It is seen that results become constant when L_3 exceeds 2,000 to 3,000 ft, or in this case, about 20 to 30 times the thickness of the pervious substratum. It would appear that such a ratio should accurately model infinitely long foundations; however, users are cautioned to make their own parametric studies for cases where accuracy is critical. Users are

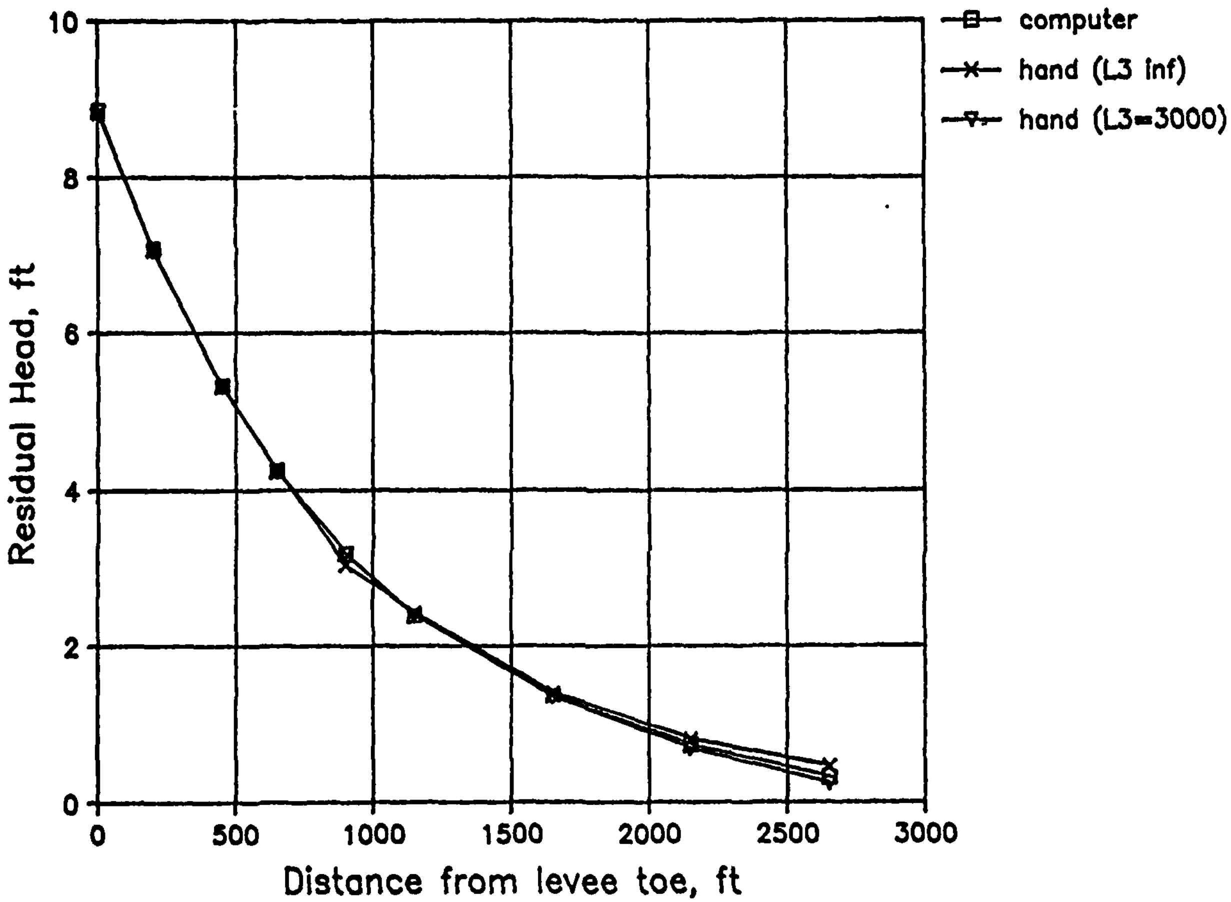


Figure 10. Residual head versus distance from levee toe, file DATACHK

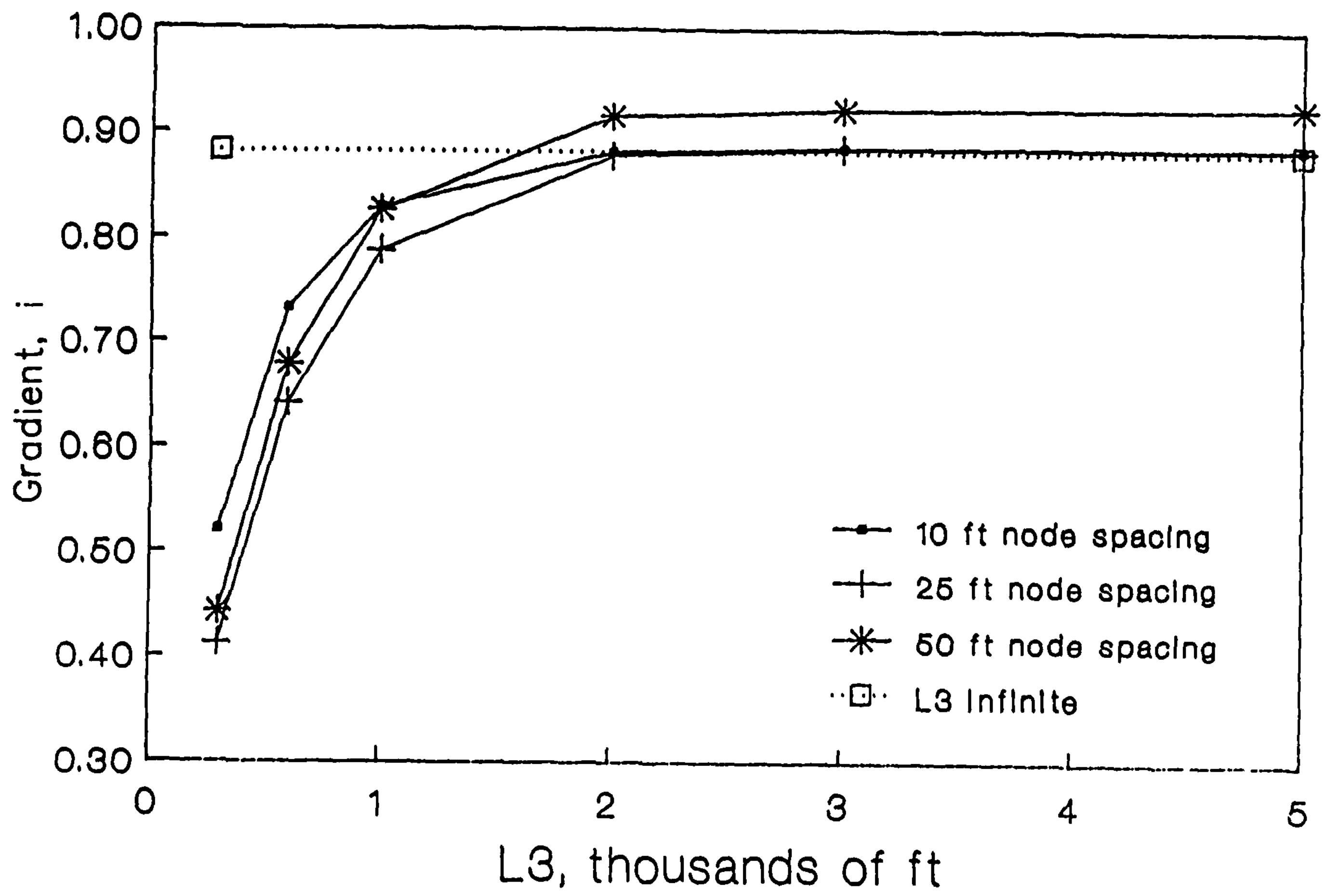


Figure 11. Gradient versus L_3 , file DATACHK

further cautioned that the distance to effective seepage exit, x_3 , is a mathematical concept used in conventional analysis, and not any measure of levee geometry. Specifying the last vertical section at some calculated x_3 distance will generally result in calculated gradients that are too low, as some seepage always in fact exits the blanket beyond the x_3 distance.

Comparison to Program LEVSEEP

29. A computer program package entitled LEVSEEP has been developed under contract to WFS by Jaycor, Inc., (Cunny, Agostinelli, and Taylor 1989). The program LEVSEEP performs underseepage analysis for the traditional model of uniformly thick layers and uniform properties. The program also performs berm design and well design calculations and cost estimates. The validation for LEVSEEP (Cunny, Agostinelli, and Taylor 1989) provided comparative solutions for five example problems worked by hand and by computer. Four of these problems were analyzed using LEVEEMSU to provide further program verification.

30. Cunny's cross section No. 1 was for a levee on a pervious foundation with no top blanket. As LEVEEMSU requires that a top blanket be present, this cross section was not analyzed.

31. Cross section No. 2 was for a levee over an impervious top blanket and a foundation with open entrance and exits at finite distances from the levee. This cross section was analyzed using LEVEEMSU and an input file named JAYCOR2. Results are shown in Figure 12. As LEVEEMSU cannot model a zero blanket permeability, the blanket was modeled with a permeability of 1×10^{-7} ft/min, or one two-millionth of the foundation permeability. As modeled, LEVEEMSU predicted a residual head of 8.392 ft and a gradient of 1.399; the hand analysis predicted a head of 8.333 ft and a gradient of 1.389. The LEVEEMSU results exceeded the hand analysis by 0.7 percent. Table 1 presents the residual head and gradient calculated by LEVEEMSU, LEVSEEP, and hand calculations.

32. Cross section No. 3 was for a levee over a semipervious top blanket having a foundation with a finite entrance distance and an infinite exit distance. This cross section was analyzed using an input file named JAYCOR3. The finite exit distance was approximated by using an L_3 distance of 4,800 ft. R ts of the analysis are shown in Figure 13. As modeled, LEVEEMSU

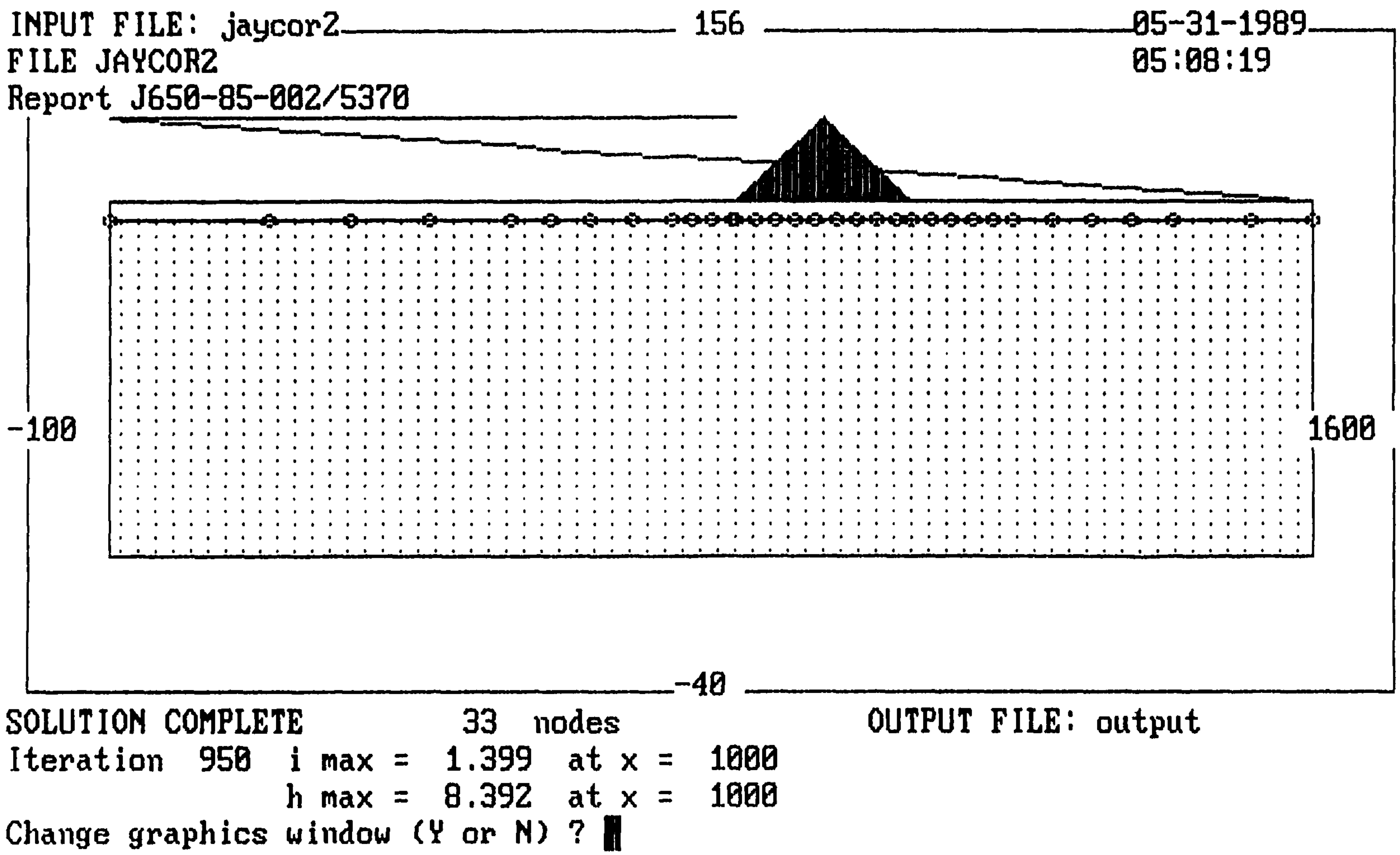


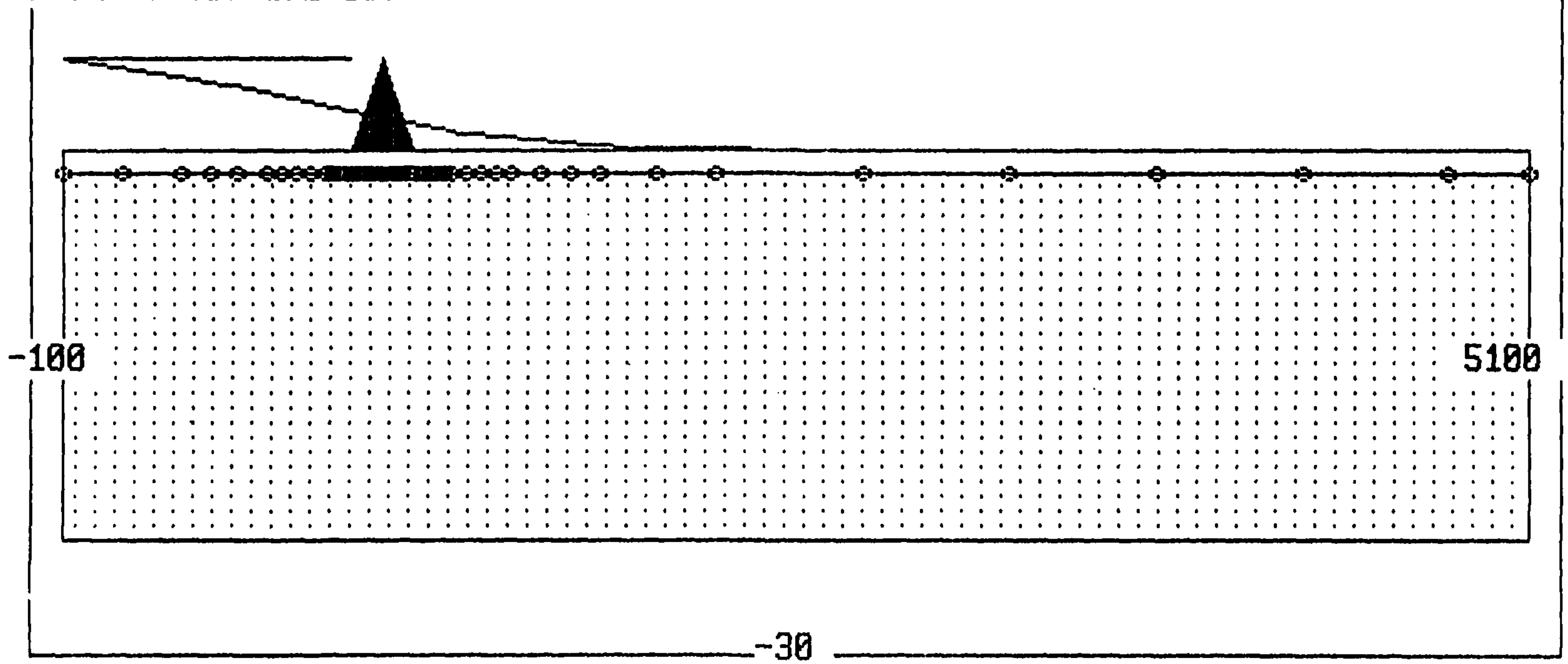
Figure 12. Copy of screen output, file JAYCOR2

Table 1

Comparison of LEVEEMSU, LEVSEEP, and Hand Calculations

	Cross-section 2		Cross-section 3		Cross-section 4	
	Residual Head h, ft	Gradient i	Residual Head h, ft	Gradient i	Residual Head h, ft	Gradient i
LEVEEMSU	8.392	1.399	7.654	1.276	6.576	1.096
LEVSEEP	8.3	1.389	7.7	1.286	6.6	1.103
Hand Calculation	8.333	1.389	7.7	1.28	6.6	1.1

INPUT FILE: jaycor3 170 05-31-1989
FILE JAYCOR3 08:37:05
REPORT J 650-002/5370



SOLUTION COMPLETE 43 nodes OUTPUT FILE: out
Iteration 874 i max = 1.276 at x = 1200
h max = 7.654 at x = 1200
Dump output to printer (Y or N) ? n
Run again (Y or N) ?

Figure 13. Copy of screen output, file JAYCOR3

predicted a residual head of 7.654 ft and a gradient of 1.276; the hand analysis predicted a head of 7,723 ft and a gradient of 1.287. The LEVEEMSU results were lower than the hand analysis by 0.9 percent.

33. Cross section No. 4 was for a levee over a semipervious top blanket having a foundation with a finite entrance distance and exit distances. This cross section was modeled using an input file named JAYCOR4. Results are shown in Figure 14. As modeled, LEVEEMSU predicted a residual head of 6.576 ft and a gradient of 1.096. The hand analysis predicted a head of 6.618 ft and a gradient of 1.103. The LEVEEMSU results were lower than the hand analysis by 0.6 percent.

34. Cross section No. 5 was for Stovall, MS, Section B-B. This section has very irregular geometry and was one of the selected prototype test sections for LEVEEMSU and its predecessor LEVEEIRR. The hand calculations were made for Section A-A at Stovall; hence, they are not compared in Table 1. Analysis of this section is shown in Part IV of this report.

Effects of Blanket Permeability

35. To assess the consistency of program behavior with respect to permeability, a series of parametric studies were performed. The data file DATACHK models a permeability ratio $k_f/k_b = 1,000$ on both the riverside and landside of the levee. The problem was altered by keeping the landside permeability and permeability ratio constant ($k_f/k_{bl} = 1,000$) and varying the riverside permeability ratio k_f/k_{br} from 1 to 1,000. Then the riverside permeability was held constant, and the landside permeability ratio changed in a similar fashion. Calculated maximum gradients are plotted versus permeability ratio in Figure 15. It is seen that the program exhibited consistent and expected behavior, with the gradient increasing with increasing riverside permeability or decreasing landside permeability, and vice versa.

Effects of Sloping Ground

36. A simple but perhaps striking illustration of the effects of irregular geometry is the case of a sloping ground surface landside of a levee. This is a commonly encountered condition where levees are founded on natural

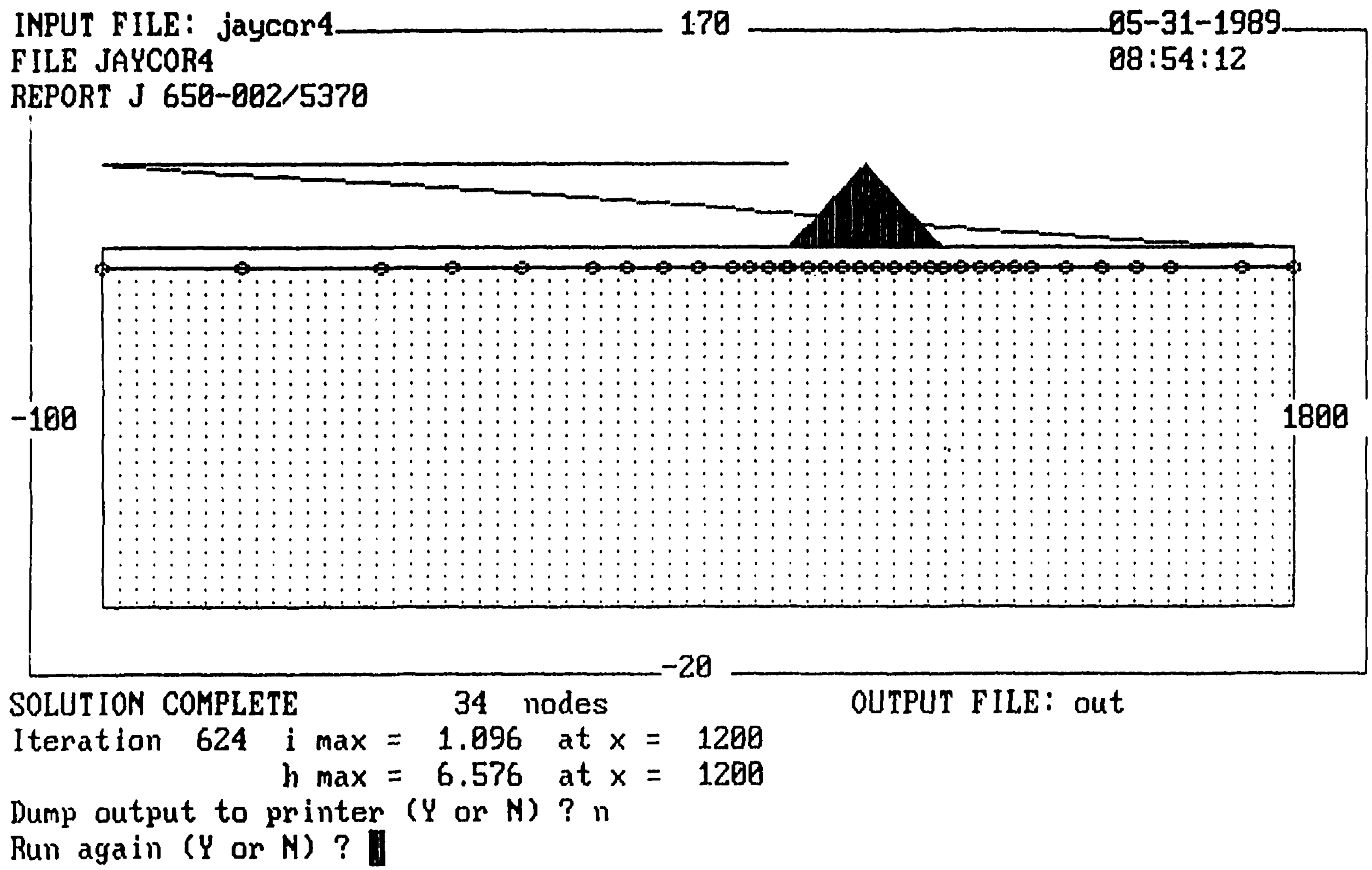


Figure 14. Copy of screen output, file JAYCOR4

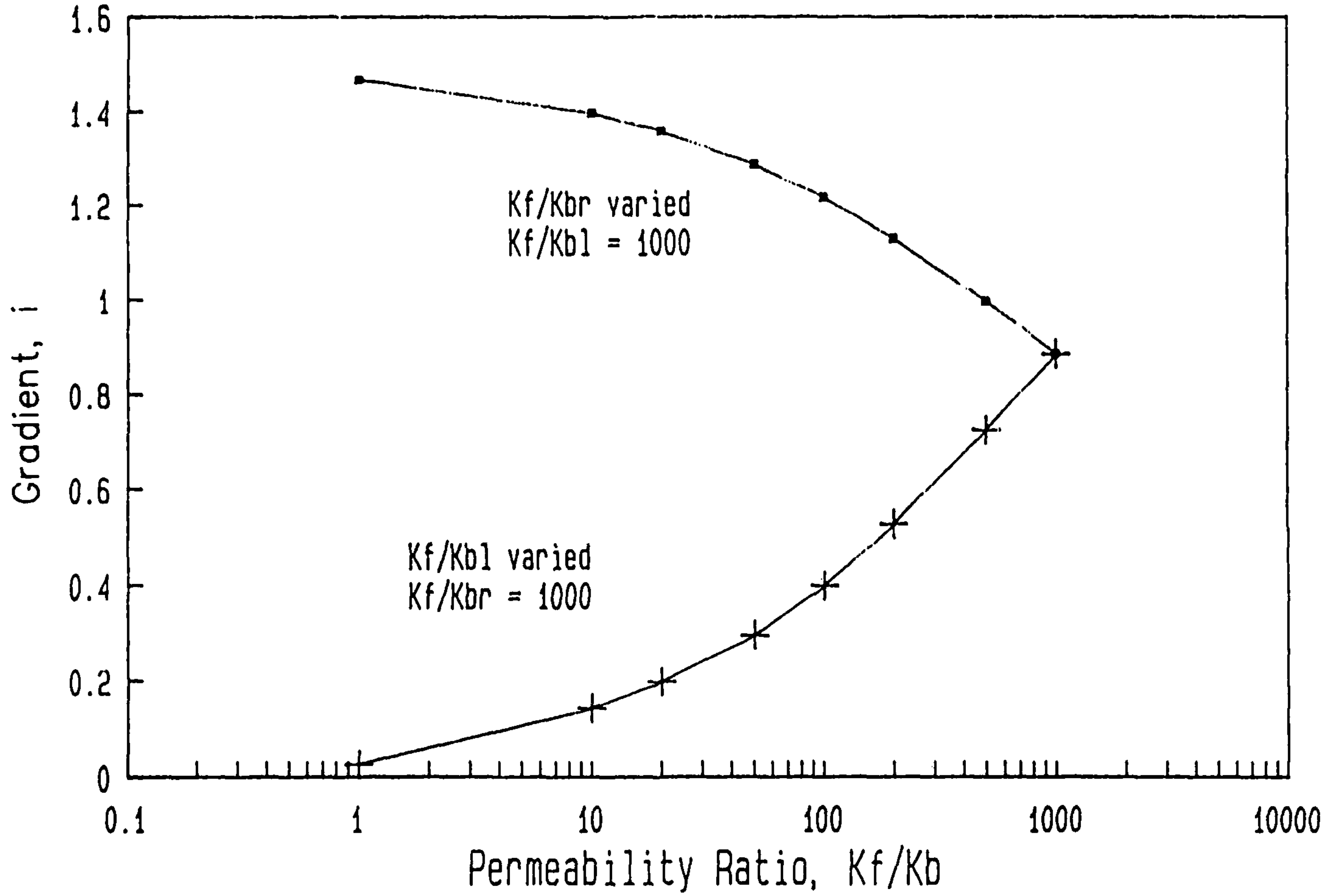


Figure 15. Maximum gradient versus permeability ratio, file DATACHK

levee deposits. To assess the effects of ground slope, a parametric study was made by successively altering the file DATACHK. The foundation and blanket thicknesses were kept constant, but the landside ground surface slope was varied from 1V on 1,000H to 1V on 50H both toward the levee and away from the levee. An example screen copy from the study is shown in Figure 16. Results are shown in Figure 17. The observed results have significant implications. It is seen that a ground slope as little as ½ to 1 percent away from the levee can lower the gradient several tenths, and similar slopes toward the levee can raise the gradient a similar amount. The observed differences from the level ground case would be sufficient to result in sand boils at sections predicted to be safe, and safe conditions at sections predicted to have boils. Conventional analysis procedures provide no means to assess such effects. It appears that many observed inconsistencies between analysis and field performance might be attributed to ground slope alone.

Effects of Ditches

37. A common problem in underseepage analysis is assessing the effects of landside ditches and determining minimum distances that ditches should be set back from a levee to provide acceptable gradients. These effects can easily be assessed using LEVEEMSU. To illustrate such analyses, a file named DATADCH (Appendix D) was created and systematically modified to vary the distance between the landside levee toe and ditch crown and to vary ditch depth. In all cases, the ditch had a 10 ft bottom width and 1V on 3H side slopes. The foundation had a substratum thickness of 65 ft and a top stratum thickness of 15 ft. Both constant blanket permeability (PERMFLAG = "CONST") and variable (PERMFLAG = "CURVE") blanket permeability conditions were modeled. A typical screen output for this problem is shown in Figure 18. Results of the study are summarized in Figure 19. For a 5-ft-deep ditch more than about 300 to 350 ft from the levee toe, the gradient at the levee toe (0.61) exceeds the gradient at the ditch for the conditions modeled. A 10-ft-deep ditch results in excessively high gradients even at distances as far as 600 ft from the levees. The sections modeled with variable ("CURVE") blanket permeabilities have lower permeability values except at the ditch. Using the curve option, the specified permeability is for a 10-ft-thick blanket in the ditch; the

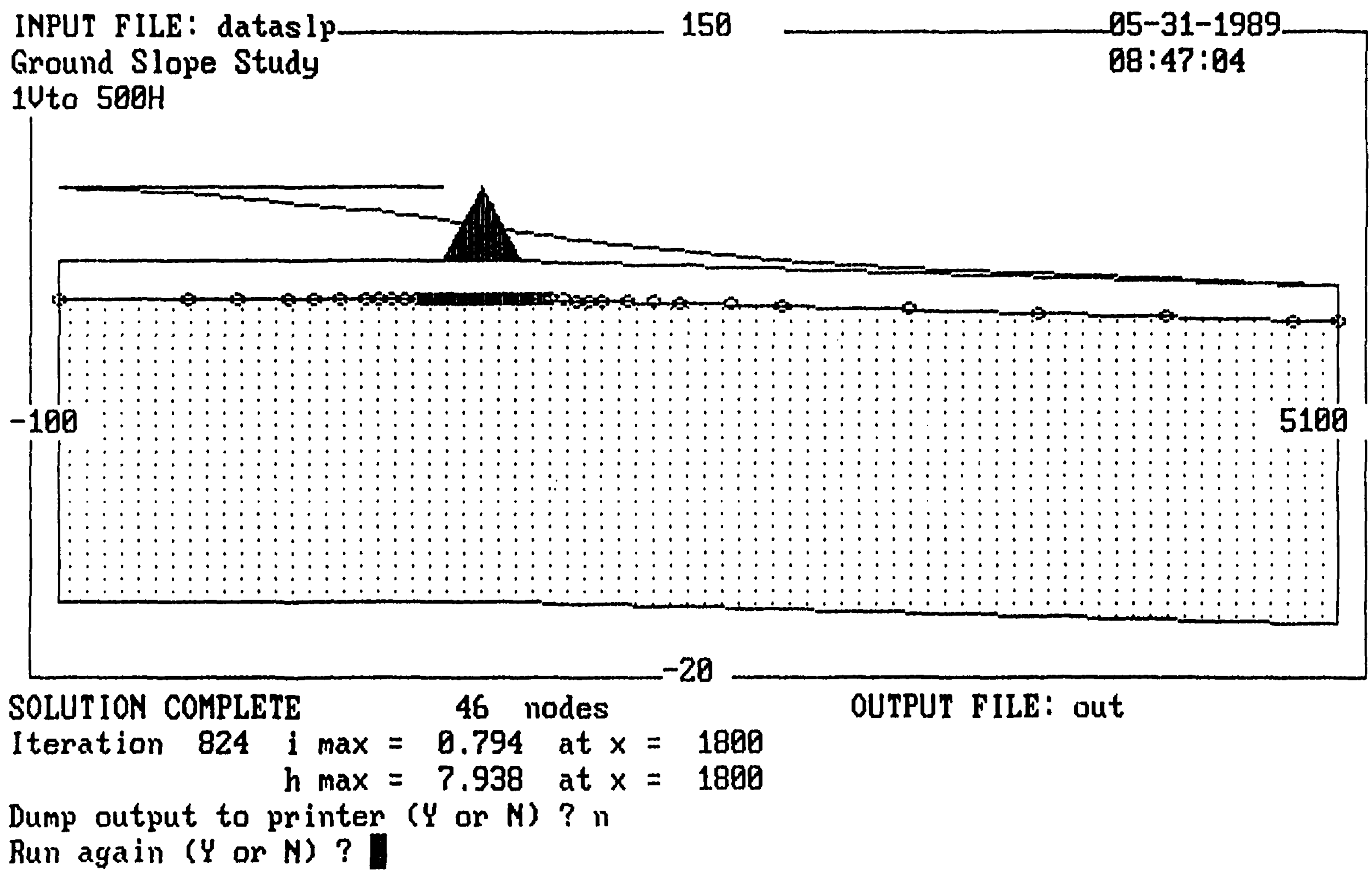


Figure 16. Copy of screen output, ground slope analysis

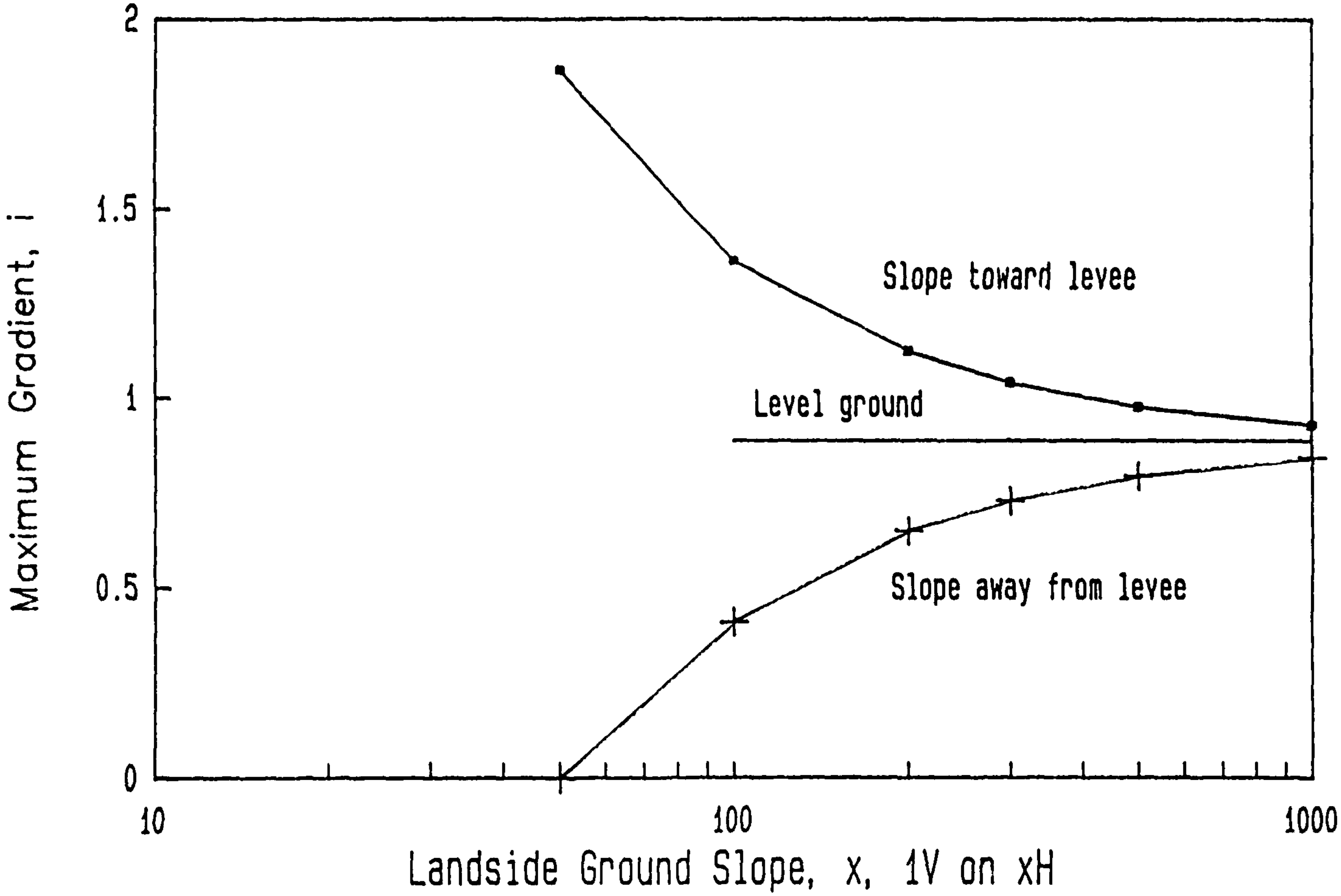


Figure 17. Maximum gradient versus landside ground slope, file DATACHK

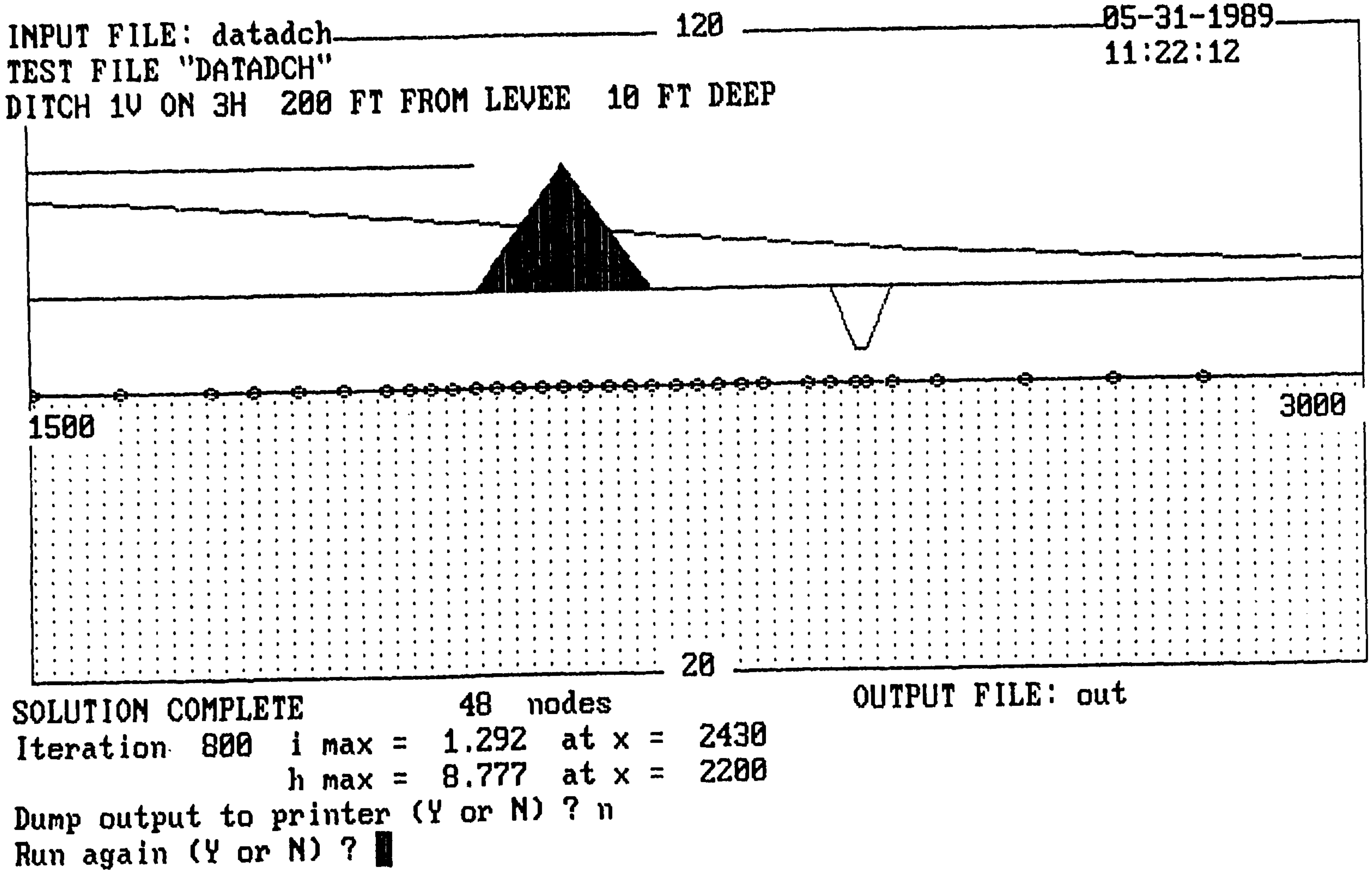


Figure 18. Copy of screen output, file DATADCH

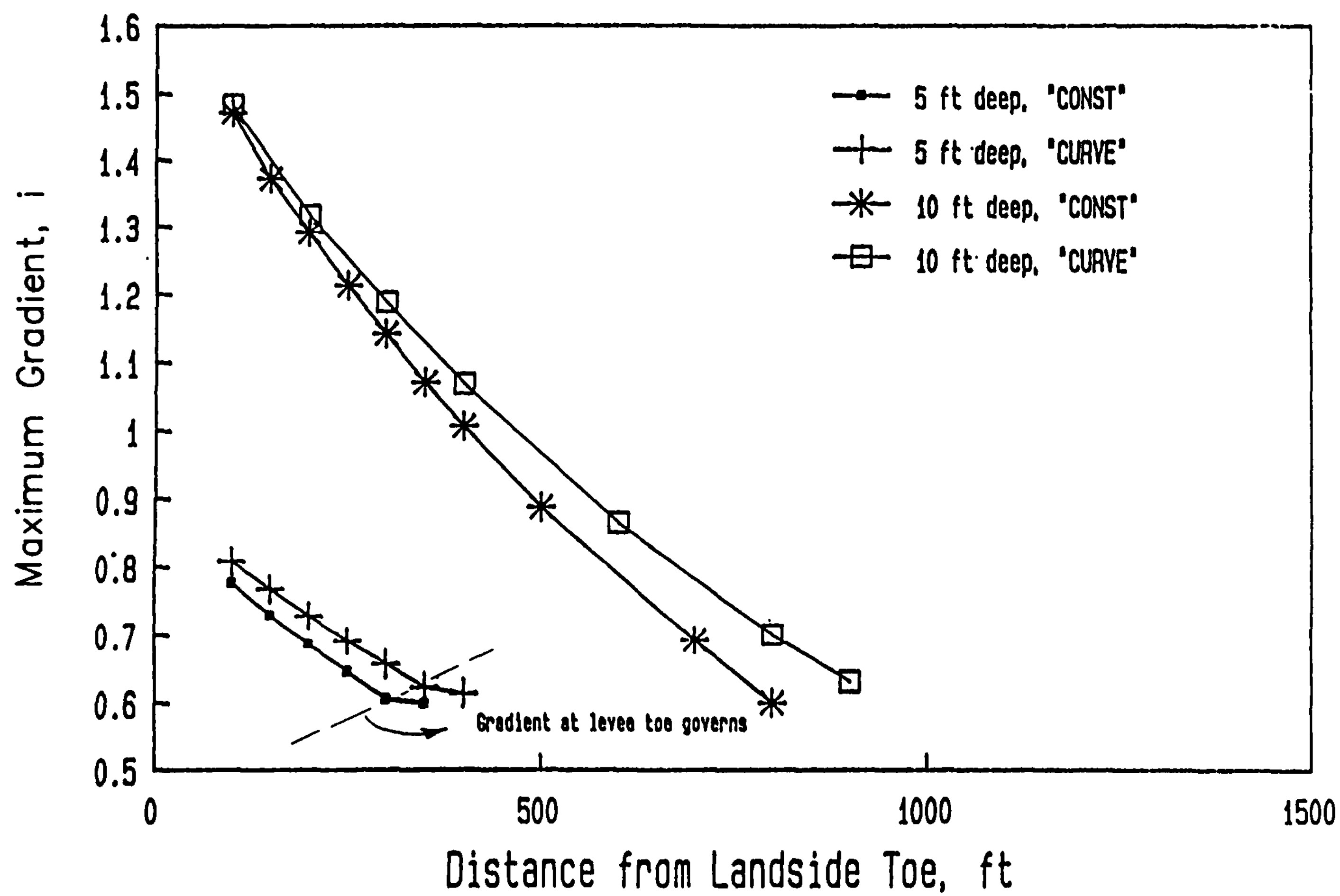


Figure 19. Maximum gradient versus ditch size and location

program adjusts the k for a thickness greater than 10 ft to the permeability for a 10-ft blanket at the ditch and a 15-ft blanket away from the ditch.

Effects of Riverside Borrow Pits

38. Another common analysis problem is assessing the effects of borrow pit distance and depth on underseepage conditions for new levees or the effects of borrow pit enlargement for raising existing levees. This problem is essentially the same as the ditch problem, but usually alters geometry on the riverside of the levee. Again, LEVEEMSU provides a tool to rationally assess such changes. The results of an example are shown in Figure 20. The geometry of file DATACHK was modified to model a riverside borrow pit 300 ft wide and 5 ft deep with 1V on 3H side slopes at different distances from the levee toe. These results are shown in Figure 21. It is seen that moving a borrow pit closer to the levee increases the gradient as expected, but the effect is much less severe than cutting ditches on the landside.

Effects of Relief Wells

39. As stated in Part II, LEVEEMSU provides the capability to approximately model the effects of a line of relief wells by specifying the piezometric head at one landside location. The program calculates the well flow per foot of levee required to reduce the average piezometric elevation in the well line to the specified value. The designer must then design a well system consistent with these results. Relationships obtained between piezometric elevations and well flow do not include hydraulic losses or partial penetration effects at individual wells. They should, however, be useful for preliminary assessments of the need for wells and likely numbers and spacing.

40. To assess the program's behavior, two parametric studies were performed using the input file DATAWELL, which is essentially the file DATACHK modified to specify a well line at the levee toe. In the first study, the specified piezometric elevation in the well line was varied. Results are shown in Figure 22. In this figure, both maximum gradient and well flow are plotted versus the specified average head at the well line. Results of such analysis can be used for preliminary design. For example, if it is desired to

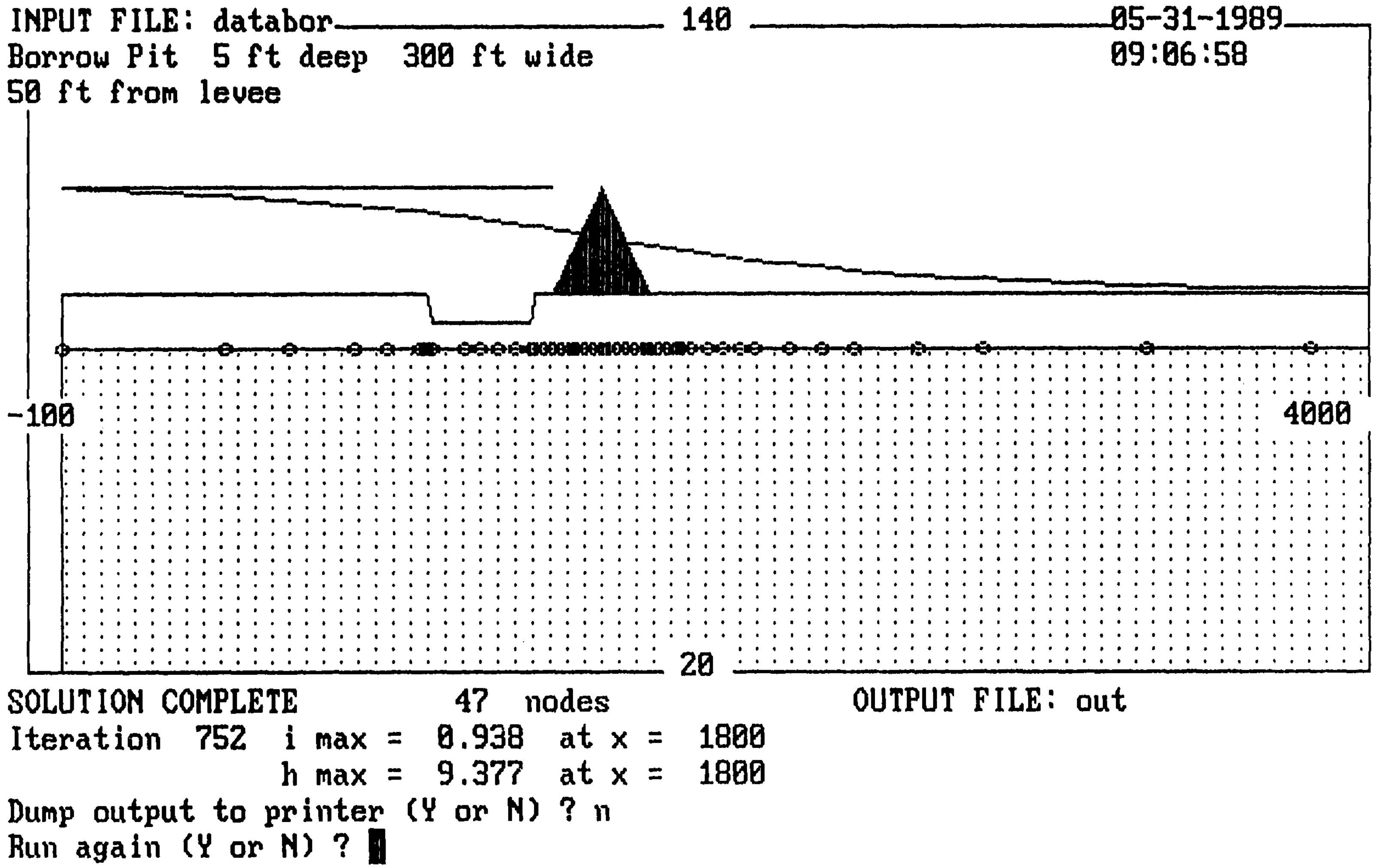


Figure 20. Copy of screen output, borrow pit study

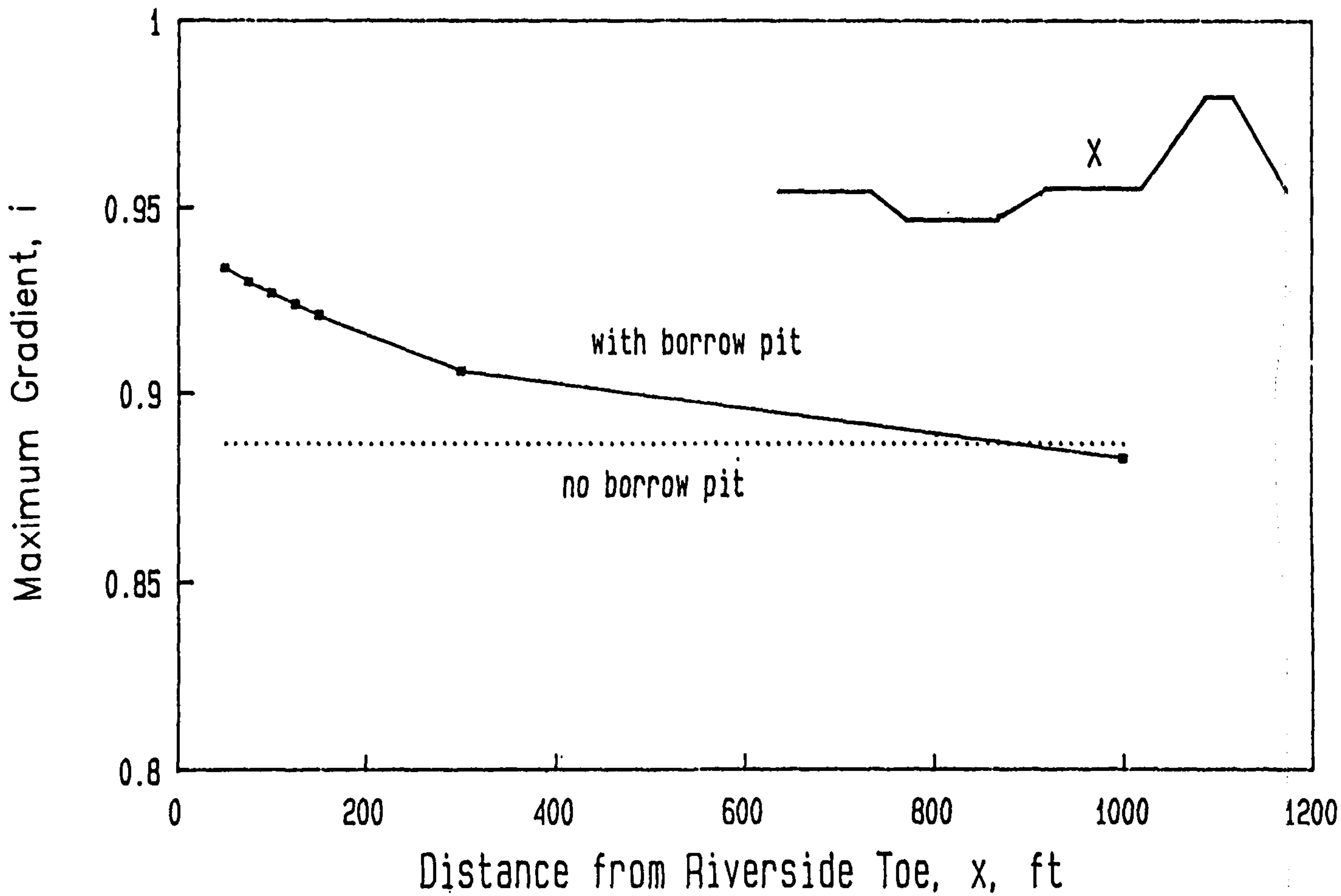


Figure 21. Results of borrow pit study

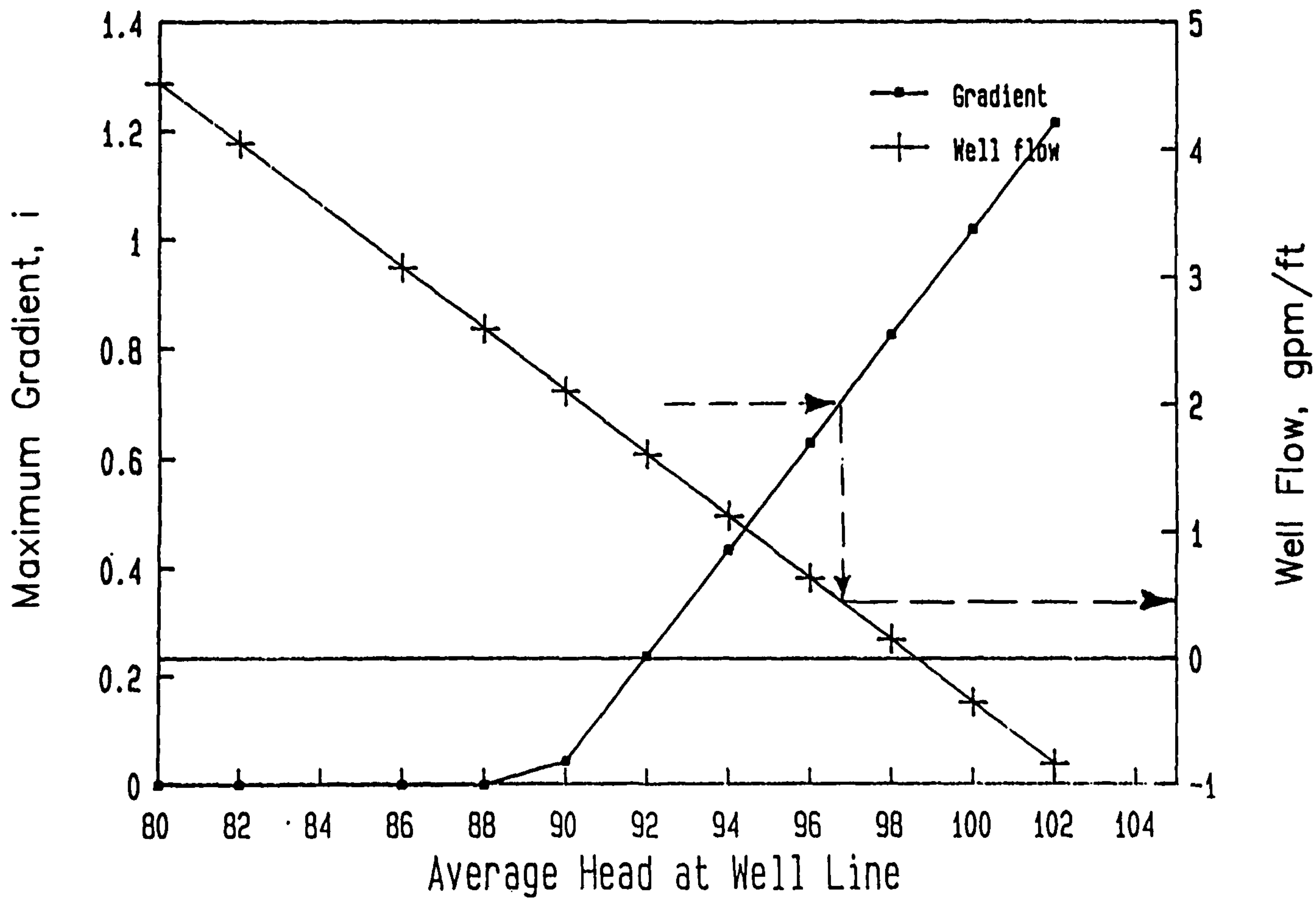


Figure 22. Maximum gradient and well flow versus average head in well line, file DATAWELL

reduce the gradient to 0.7, the figure shows that a well system must be designed that will reduce the average piezometric elevation the well line to el 97. Working from that elevation, the system must be capable of passing approximately 0.5 gal/min per ft of levee. The specified piezometric elevation resulting in zero well flow is 98.87 ft, matching the residual head of 8.87 ft obtained for the analysis of DATACHK without wells. In the second parametric study, the specified piezometric elevation was maintained constant and the foundation permeability was varied. Results are shown in Figure 23. As expected, well flow varies in proportion to the foundation permeability with only a minor change in gradient.

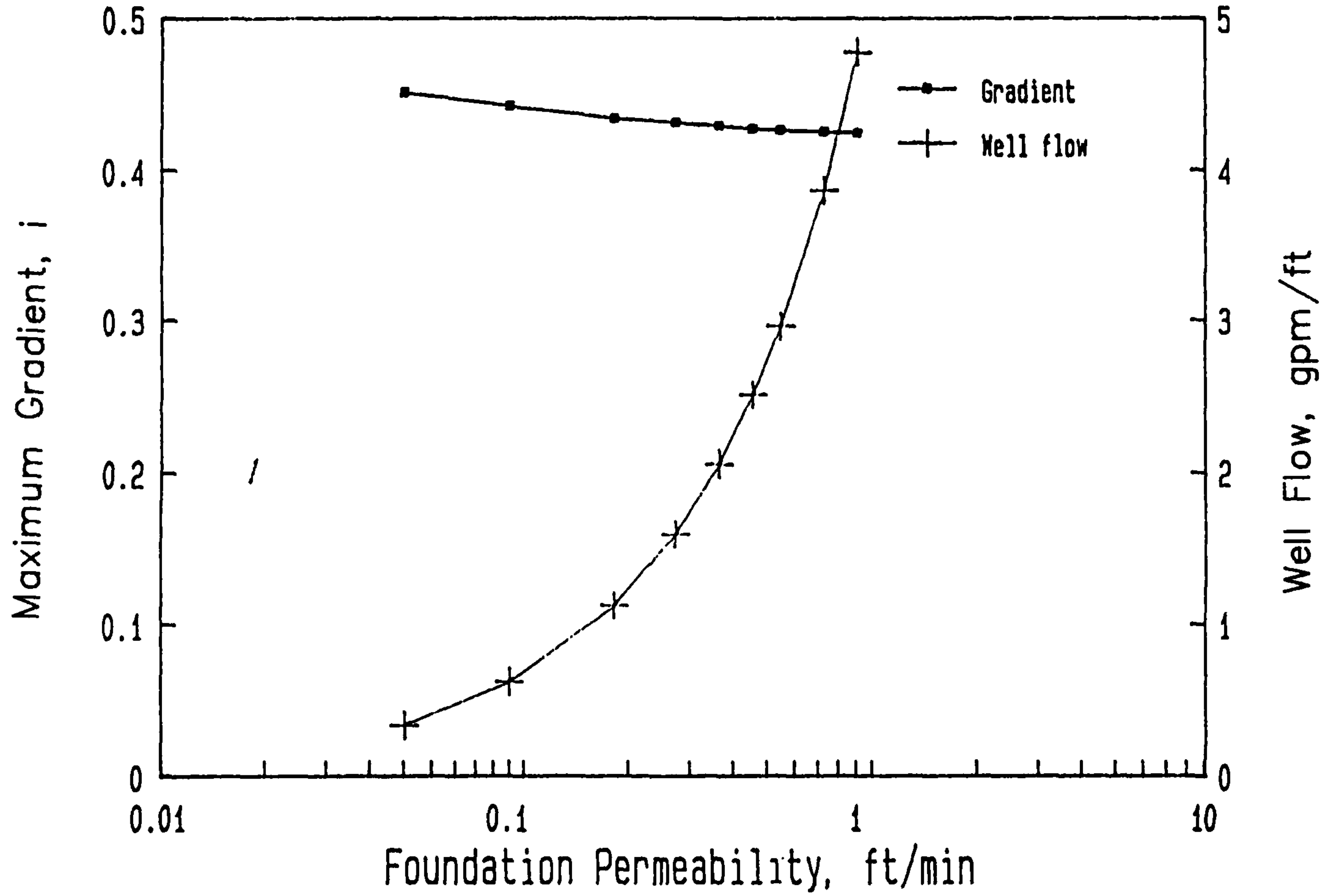


Figure 23. Maximum gradient and well flow versus foundation permeability, file DATAWELL

PART IV: ANALYSIS OF PROTOTYPE LEVEE REACHES

41. Several actual levee reaches had been analyzed using LEVEEIRR, the predecessor of LEVEEMSU, to provide comparisons of predicted versus actual performance (Wolff 1987). Certain of these reaches have been reanalyzed using LEVEEMSU. These reaches had previously been selected as having relatively complete and reliable piezometric data as well as irregular foundation conditions.

42. As any observed piezometric condition can, in theory, be matched to the results of analysis if one assumes the right set of parameters, these analyses provide only a partial check of program accuracy. In the analyses reported herein, the foundation permeability was fixed and the permeability values for the landside and riverside blankets were systematically varied until a reasonable match was obtained between predicted and measured piezometric data. Assuming the program provides accurate solutions, these analyses can be used to estimate field permeability ratios, landside and riverside, which in turn can be used in the design of seepage control measures.

Rock Island District, Hunt, Piezometric Range B

43. This piezometer range is located on the east bank of the Mississippi River about 25 miles upstream of Quincy, IL, in the pool of Lock and Dam No. 20. Data at this piezometer range has previously been analyzed by Cunny (1980) and Wolff (1987). A cross section of the site is shown in Figure 24; the modeled cross section is shown in Figure 25. Irregularities in the profile include an irregular landside ground elevation approximately 5 feet higher than the riverside and a blanket of variable thickness.

44. Cunny's previous analysis assumed uniformly thick blankets (but different thicknesses and different permeabilities on opposite sides of the levee). Cunny found that observed piezometric conditions at the levee toe could be matched using permeability ratios of $k_f/k_{br} = 209$ and $k_f/k_{bl} = 64$ Thus, $k_{bl}/k_{br} = 3.26$. The previous analysis by Wolff (1987) using LEVEEIRR allowed for irregular geometry but assumed equal blanket permeabilities on both sides of the levee. This analysis showed that a permeability ratio

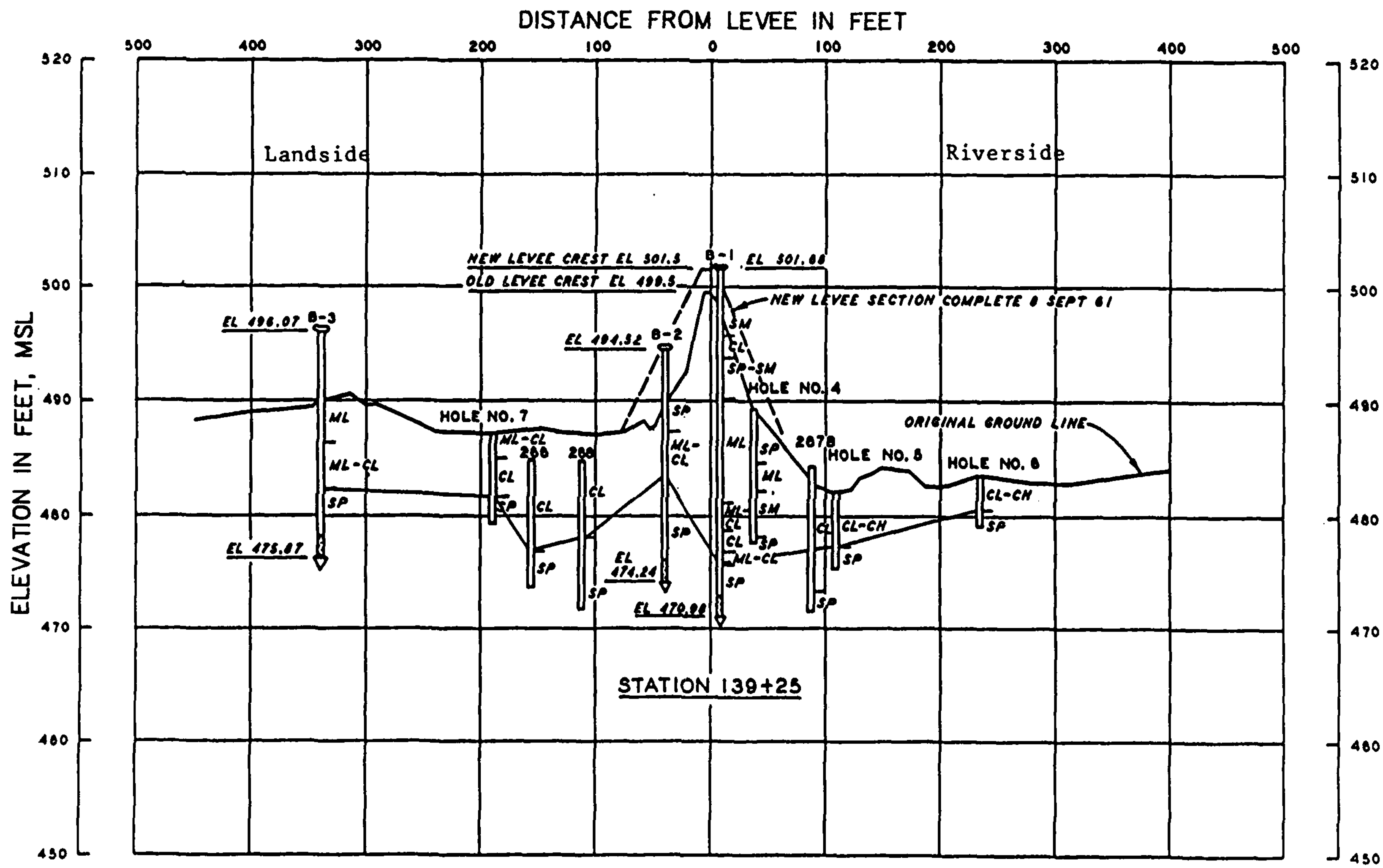


Figure 24. Actual cross section, Hunt (after Cunny, 1980)

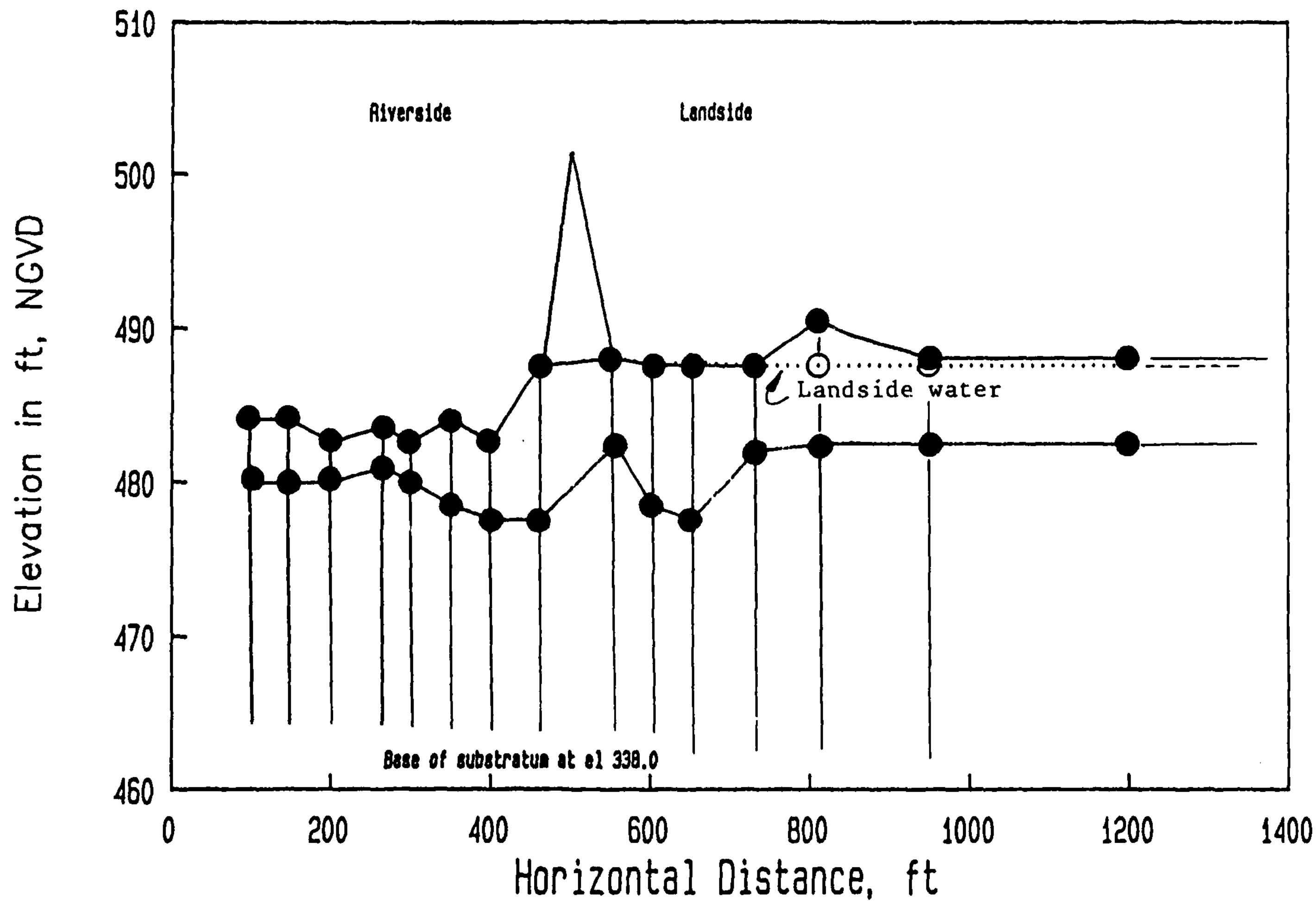


Figure 25. Modeled cross section, Hunt

k_f/k_b between 20 and 64 provided a reasonable match to observed data, both at the levee toe and away from the toe.

45. A copy of a typical screen output from the LEVEEMSU analysis is shown in Figure 26. The foundation permeability was taken as 0.128 ft/min (640×10^{-4} cm/sec). A riverside permeability ratio of $k_f/k_{br} = 64$ was assumed and the landside permeability ratio was varied. Actual piezometer data represent river stages of 492.54 ft (1961), 496.13 ft (1961), and 499.0 ft (1973). It was found that a ratio $k_f/k_{bl} = 4.27$ provided a reasonable match to the observed conditions at piezometers B-1 and B-2, as shown in Figure 27. The ratio blanket permeabilities, k_{bl}/k_{br} is found to be 15. The flat response of piezometer B-3 in the computer model arises from apparent differences in the field permeability values from the levee toe to the vicinity of B-3. The blanket must be modeled as very pervious to match observed conditions near the levee toe; when this is done, residual heads are quite low at points away from the levee, as is evident from Figure 26. Reducing the landside blanket permeability would improve the match at B-3 but result in an overprediction of the residual head near the levee toe.

46. In performing this analysis, it became quite apparent that predicted piezometric elevations remote from the levee are quite sensitive to the specified landside water elevation. Where the landside water elevation is modeled coincident with ridges above the prevailing ground, the model will produce downward flow from the ridges to the aquifer, causing high piezometric levels. Where the ridged are modeled as being above the landside water elevation, more reasonable results are obtained.

47. For a river stage at the crest of the levee, el 501.5 ft, the computer predicts a maximum gradient of 0.385, occurring at the landside levee toe.

48. Permeability ratios obtained from this analysis are even lower than the relatively low values previously calculated. Since a perfect match between predicted and observed piezometric elevations cannot be made simultaneously for all piezometers and all river stages, these values should only be considered representative of the actual order of magnitude. However, one can conclude from both these and previous analysis that the field ratio k_f/k_{bl} is in the range of 4 to 80 and the ratio k_f/k_{br} is in the range of 50 to 250. The top blanket at Hunt appears to be quite pervious.

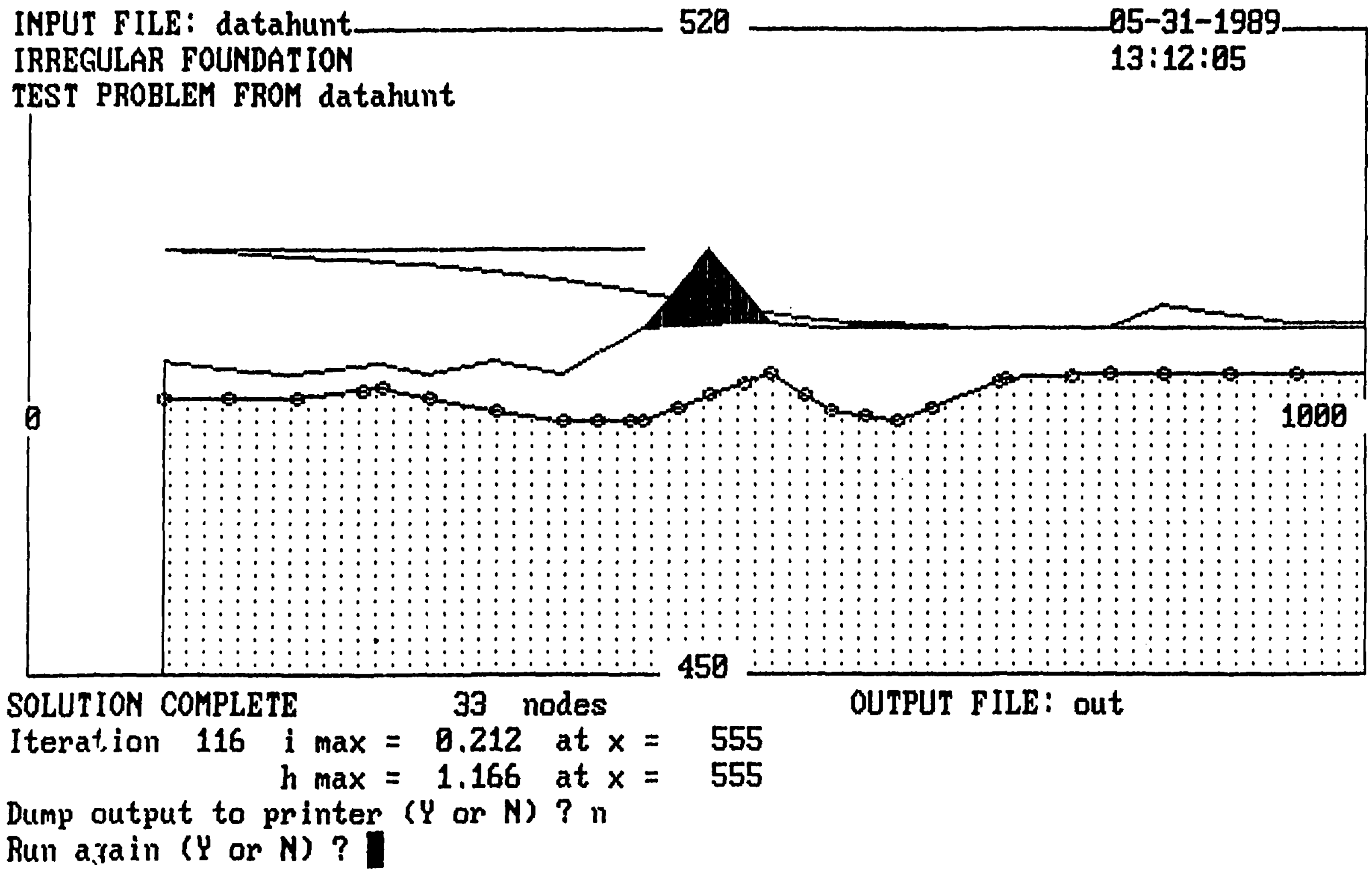


Figure 26. Copy of screen output, Hunt

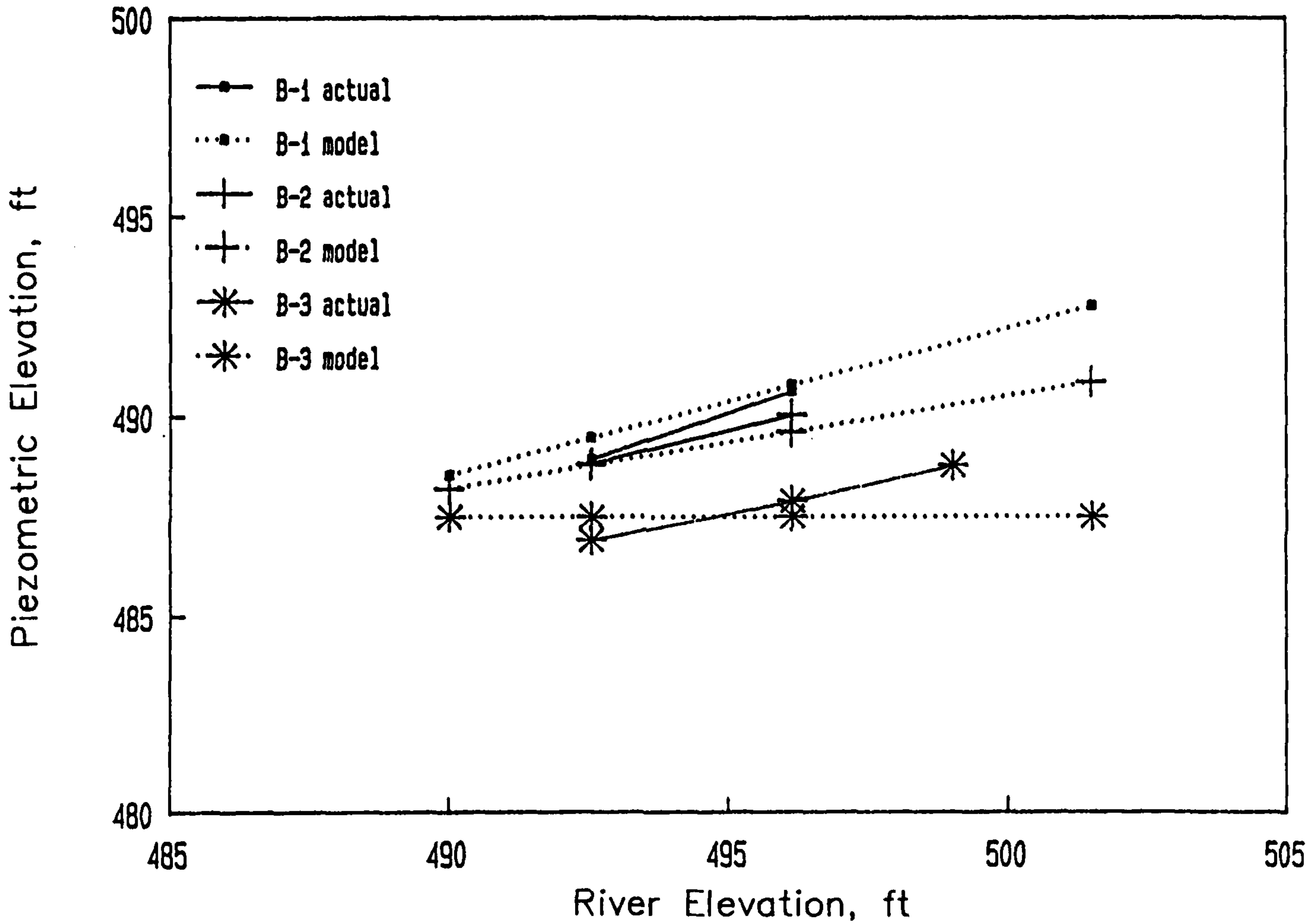


Figure 27. Piezometric elevations versus river elevation, Hunt

Memphis District, Commerce, MS, Line H

49. This piezometer range is located about 10 miles north of Tunica, MS. The levee is located about 2,200 ft from the Mississippi River on terrain characterized by numerous ridges, swales, and ditches. Heavy seepage damage was reported during the 1937 high water. Data at this piezometer range has previously been analyzed by WES (1964) and Wolff (1987). The actual and modeled cross sections at the site are shown superimposed in Figure 28. Foundation conditions include a deep riverside borrow pit that leaves a blanket of only a few feet of silt, and a very thick clay blanket starting about 1,600 ft landward of the levee.

50. Previous analyses found permeability ratios of $k_f/k_{br} = k_f/k_{bl} = 580$ (WES 1964) and 514 (Wolff 1987).

51. A copy of a typical screen output from LEVEEMSU is shown in Figure 29. The foundation permeability was taken as 0.18 ft/min (900×10^{-4} cm/sec). The blanket permeability values were generated using the variable permeability option described in Part II of this report. On the riverside, a curve number of 0.0007 was specified, corresponding to silt; on the landside, a curve of 0.0005 was specified, corresponding to clay. The program calculates the blanket permeability at each node using the blanket thickness at that node. Results of the present analysis are compared with actual piezometric data in Figure 30; piezometer data correspond to river stages of 202.7 and 205.0 ft (May 18 and 22, 1961). It is of interest to note that the variable permeability option provided a reasonably good match to actual performance on the first try.

52. For a river stage at the levee crest, el 220.2 ft, the computer model predicts a maximum gradient of 1.06 at $x = 330$ ft landside of the centerline, the location of the landside berm toe and piezometer 9-x.

Memphis District, Stovall, MS, Piezometric Line B

53. This piezometer range is located about 3.5 miles west of Stovall, MS. Seepage damage occurred at the site during the 1937 high water. Foundation conditions are shown superimposed on the modeled conditions in Figure 31. These conditions are an example of extremely dissimilar landside and riverside

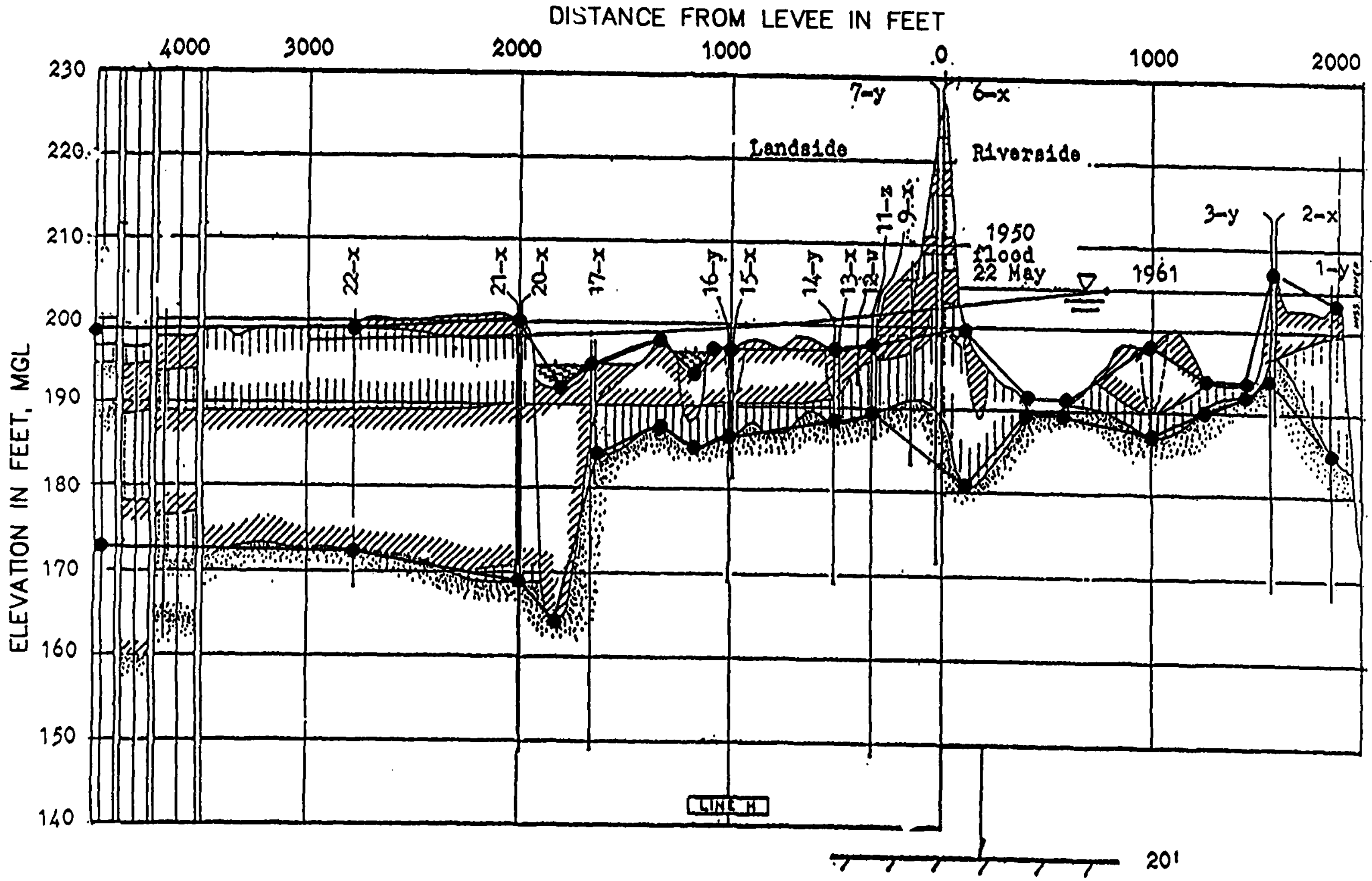


Figure 28. Actual and modeled cross section, Commerce (after WES, 1964)

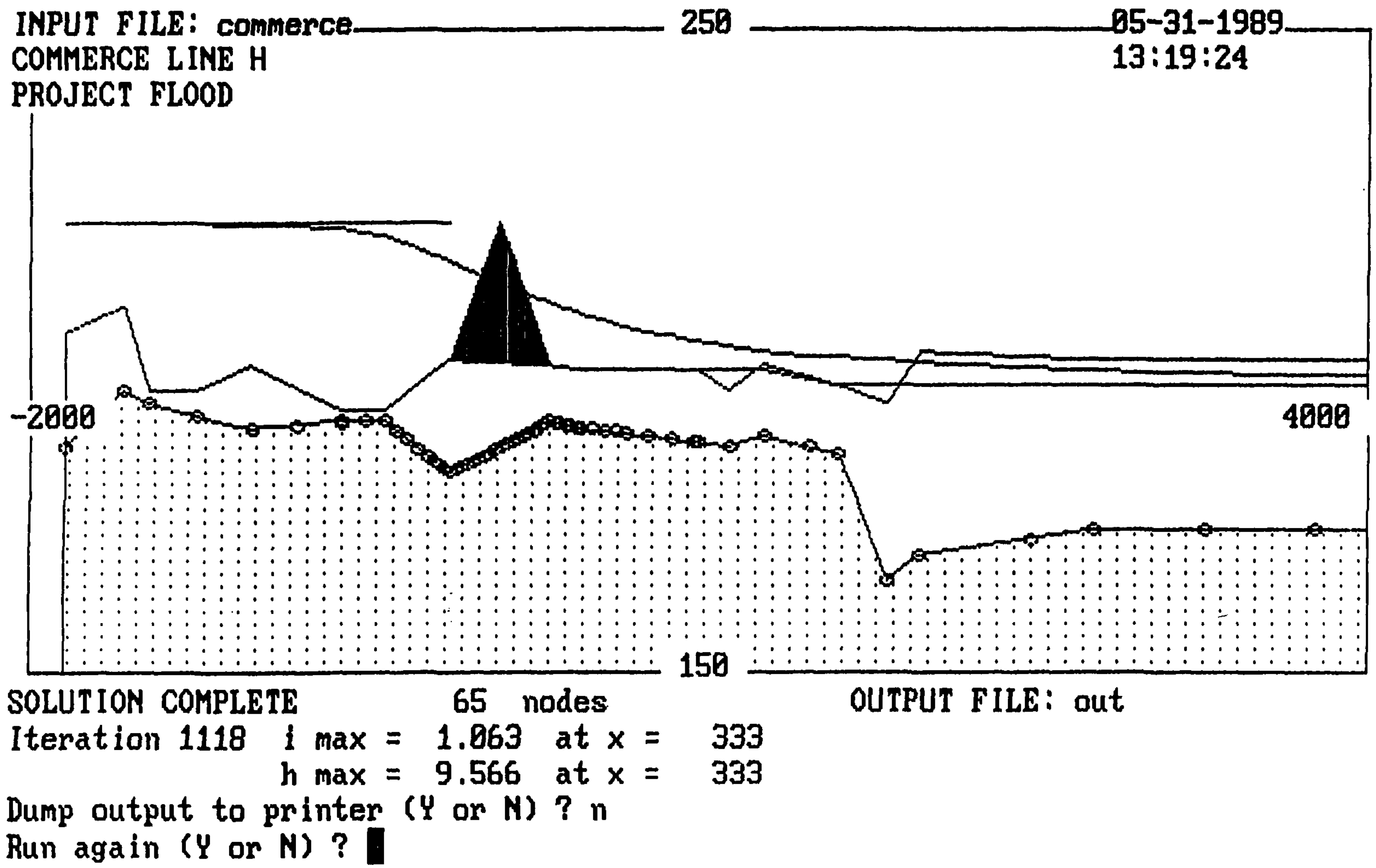


Figure 29. Copy of screen output, Commerce

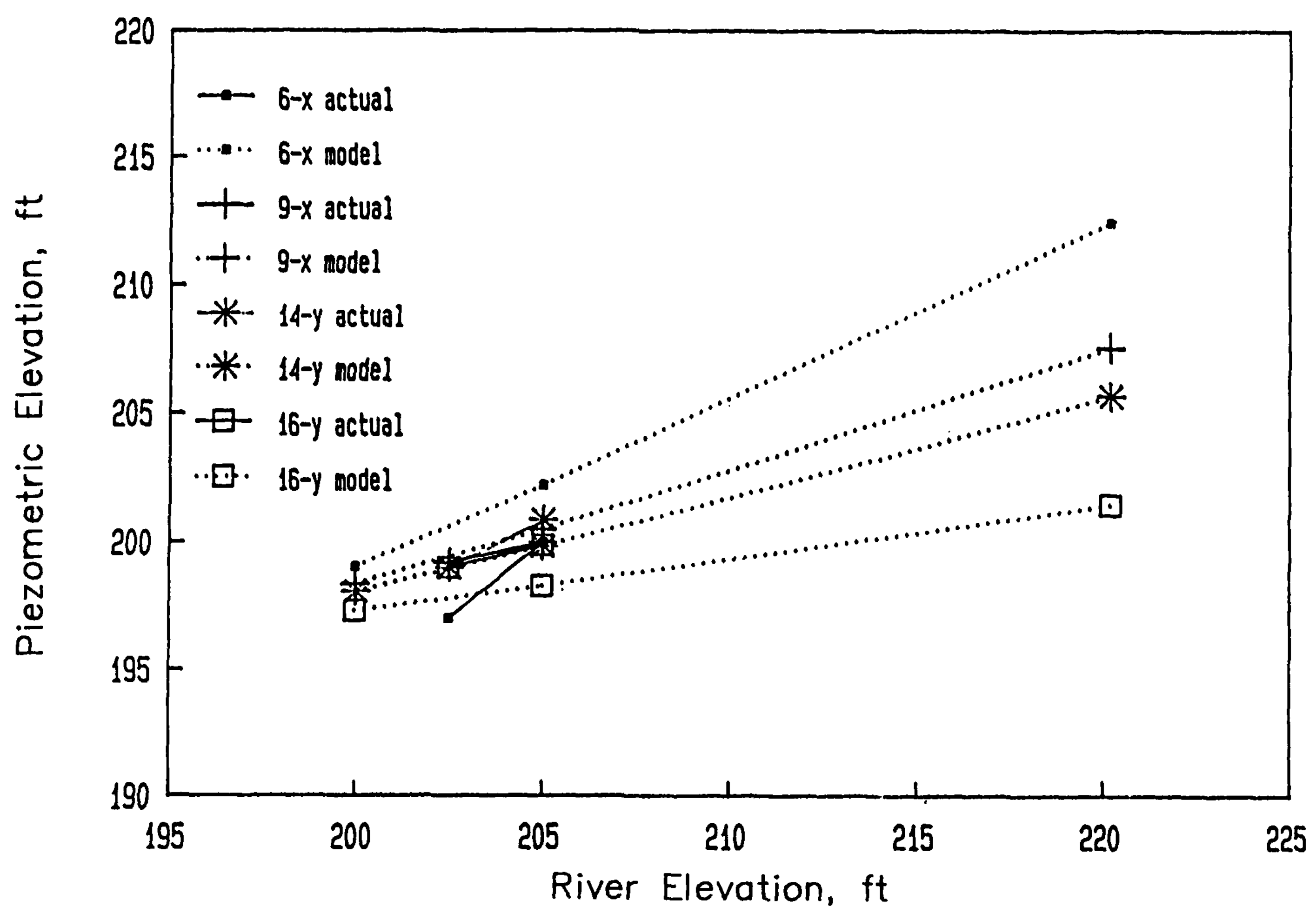


Figure 30. Piezometric elevations versus river elevation, *Commerce*

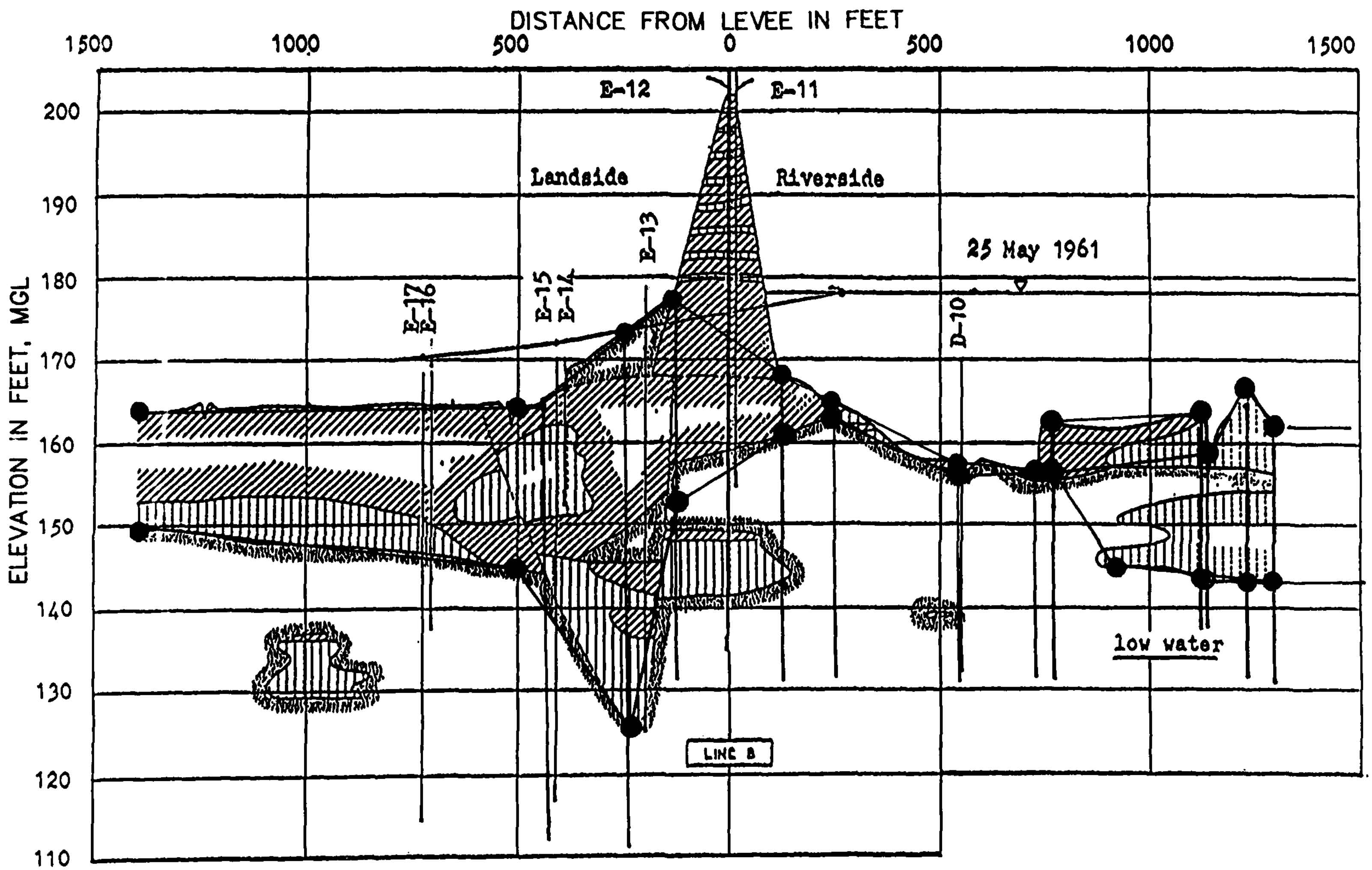


Figure 31. Actual and modeled cross section, Stovall (after WES, 1964)

blanket conditions. The riverside blanket is predominantly silt and much of it has been excavated for borrow. The riverside blanket is clay, typically 15 ft thick. A seepage berm has been constructed on the landside. Piezometric data are available for May 1961 (WES 1964).

54. Previous analysis by the WES (1964) obtained a ratio k_f/k_{bl} of 600. Previous analysis using LEVEEIRR (Wolff 1987) indicated k_f/k_{bl} ratios in the range of 432 to 1,000; however, the modeling of equal blanket permeabilities on both sides of the levee did not provide a match to observed data at several piezometers simultaneously.

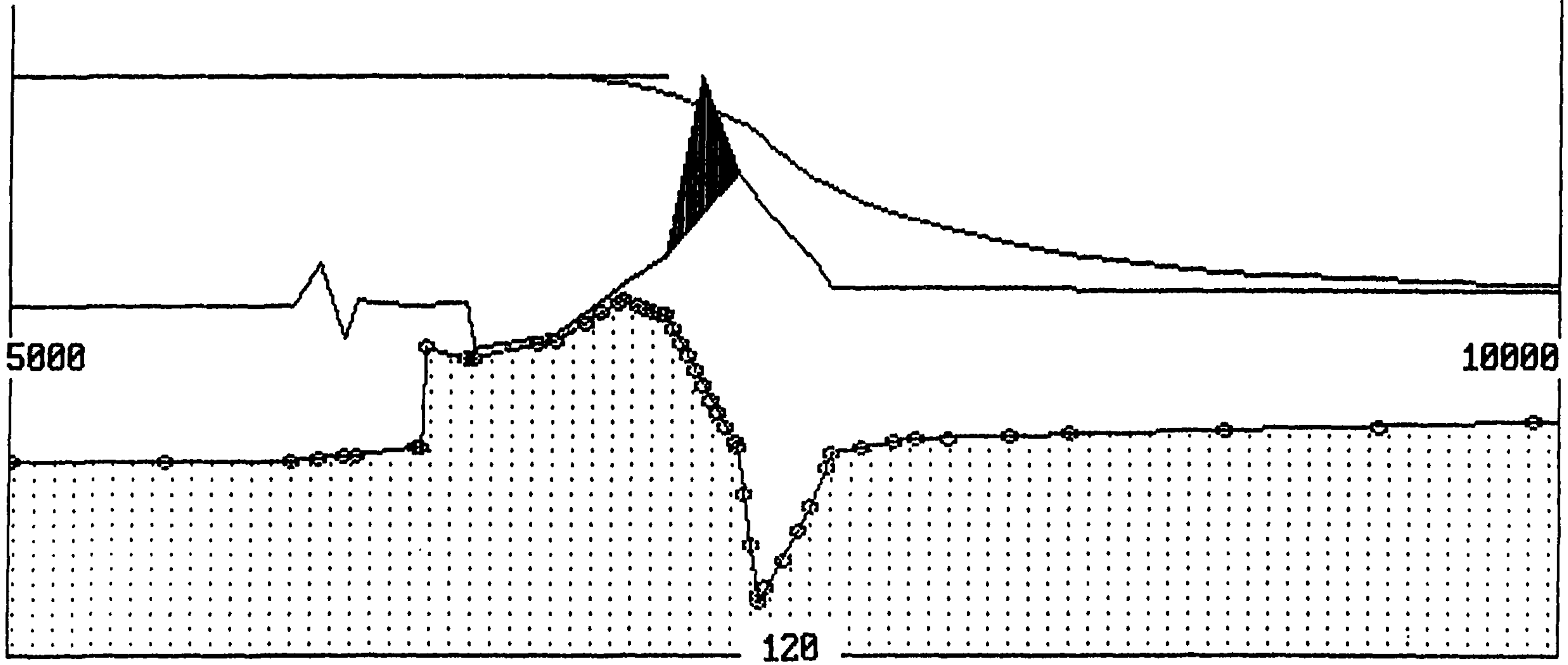
55. Using LEVEEMSU, the section was analyzed using the variable permeability option described in Part II. The best match to observed conditions was obtained using a riverside curve number of 0.0006 corresponding to a silty clay or clayey silt, and a landside curve number of 0.0004, corresponding to a clay.

56. A copy of a screen display of the modeled cross section is shown in Figure 32. Note that landside and riverside are reversed from the previous figure. The entire riverside geometry extends more than a mile to the river; however, the display has been "windowed" to show more detail near the levee. The permeability curve numbers stated above were found to yield predicted piezometric conditions that match observed data from four piezometers at greatly different distances from the levee, generally within less than 1 ft. Furthermore, the match was obtained with only a few trials, by making minor adjustments in the curve number. The results of the computer model are compared to observed conditions in Figure 33. From this analysis, it appears that the proposed approximations of the LMVD permeability versus blanket thickness curves yield reasonable solutions when used with reasonably accurate geometry data.

Vicksburg District, Bolivar, MS, Piezometric Line D

57. This piezometer range is located along the east bank levee of the Mississippi River 2 miles north of Benoit, MS. The river at this site is about 8 miles from the levee; however, Bolivar Chute lies about 1,200 to 1,500 ft riverward of the levee. A range of nine piezometers, D-1 through D-9, runs

INPUT FILE: stovall 210 05-31-1989
Memphis District -- Stovall 13:28:35
flood el. 190



SOLUTION COMPLETE 66 nodes OUTPUT FILE: out
Iteration 924 i max = 0.598 at x = 7653
h max = 12.135 at x = 7653
Dump output to printer (Y or N) ? n
Run again (Y or N) ?

Figure 32. Copy of screen output, Stovall

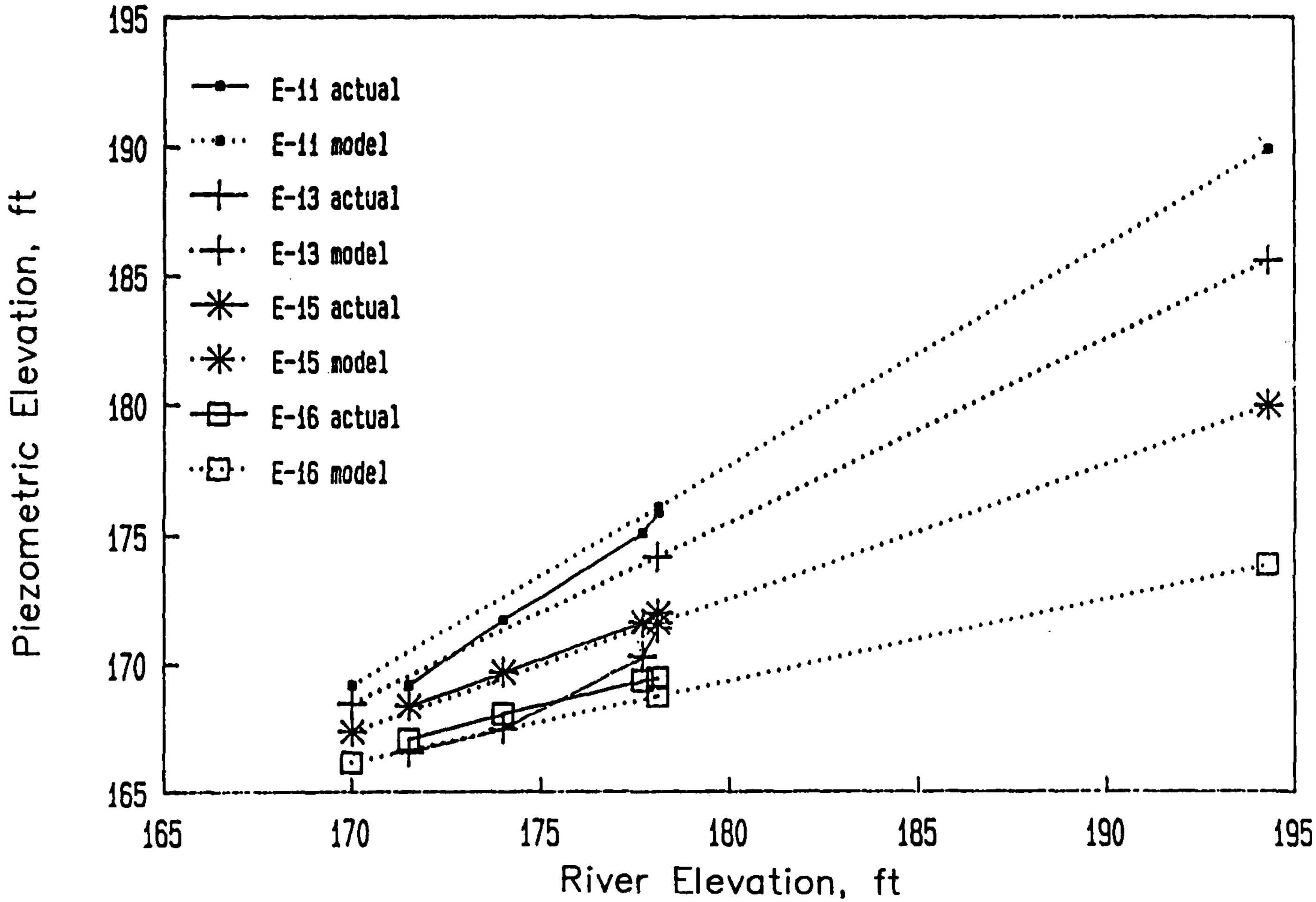


Figure 33. Piezometric elevations versus river elevation, Stovall

perpendicular to the levee at this site. A cross section of foundation conditions with the modeled cross section superimposed is shown in Figure 34. Irregularities in the profile include riverside borrow pits, landside sublevees, a landside ditch, and a massive clay-filled abandoned channel beginning about 1,000 ft landside of the levee.

58. Previous analysis by the WES (1964) found k_f/k_{bl} ratios in the range of 100 to 200. Previous analyses by Wolff (1987) found that a ratio k_f/k_{bl} of 1,000 best fit the data; however, little difference was noted for a value of 100.

59. For the present analysis, a foundation permeability of 0.24 ft/min ($1,200 \times 10^{-4}$ cm/sec) was assumed. A copy of a typical screen output from LEVEEMSU is shown in Figure 35. Actual piezometer data represent river stages of 147.0 ft (1961) and 151.7 ft (1973). More weight was given to the 1973 data in performing the analysis. It was found that ratios of $k_f/k_{bl} = 267$ and $k_f/k_{br} = 1,000$ provided a reasonable match to observed conditions as shown in Figures 36 and 37. The ratio of blanket permeabilities, k_{bl}/k_{br} is found to be 3.75.

60. For a river stage at the project flow line of el 166.4 ft, the computer model predicts a maximum gradient of 0.66, occurring at the levee toe.

61. Results of the study again support the observation that landside blanket permeability values during high water are several times higher than riverside values.

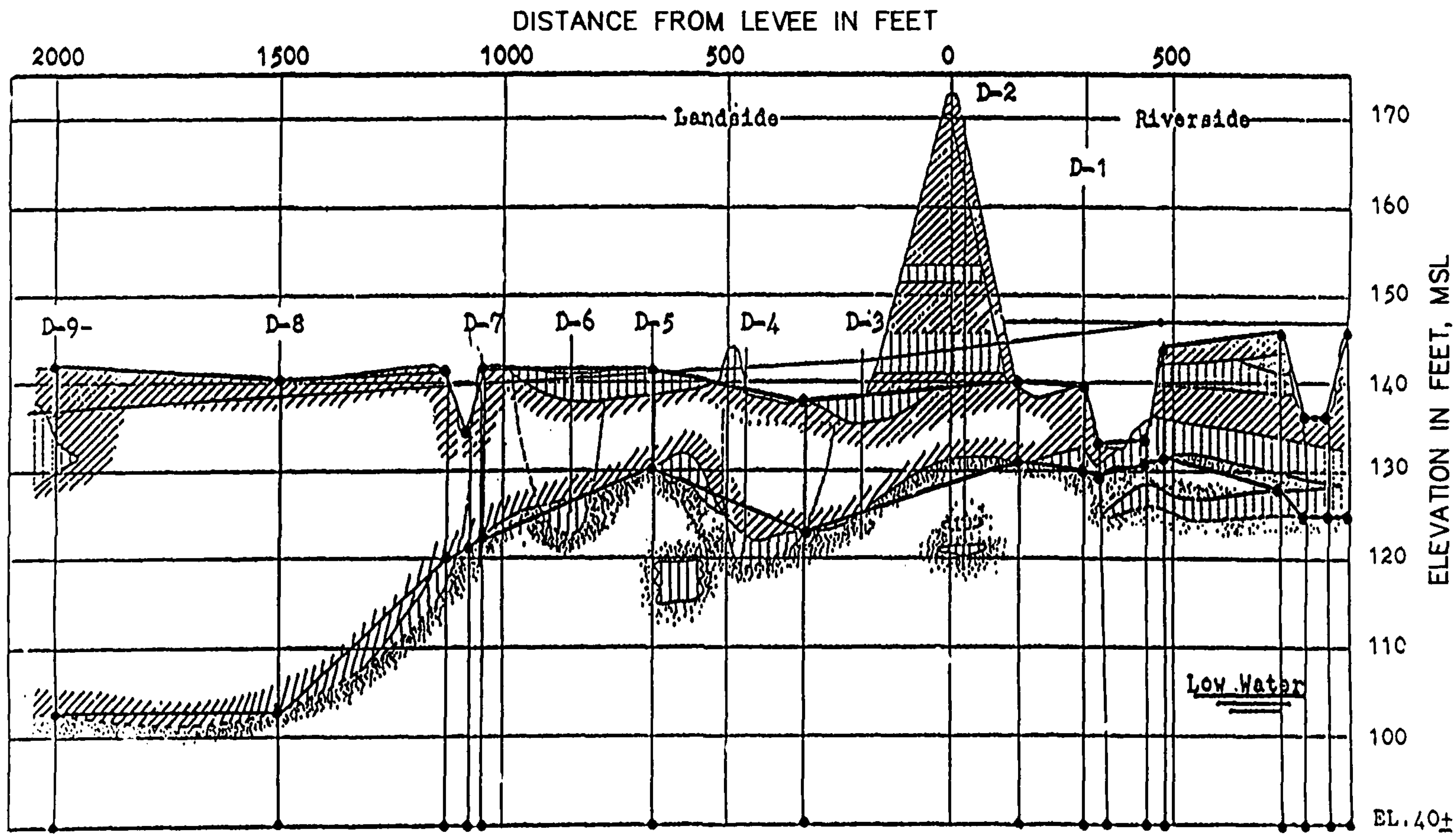


Figure 34. Actual and modeled cross section, Bolivar

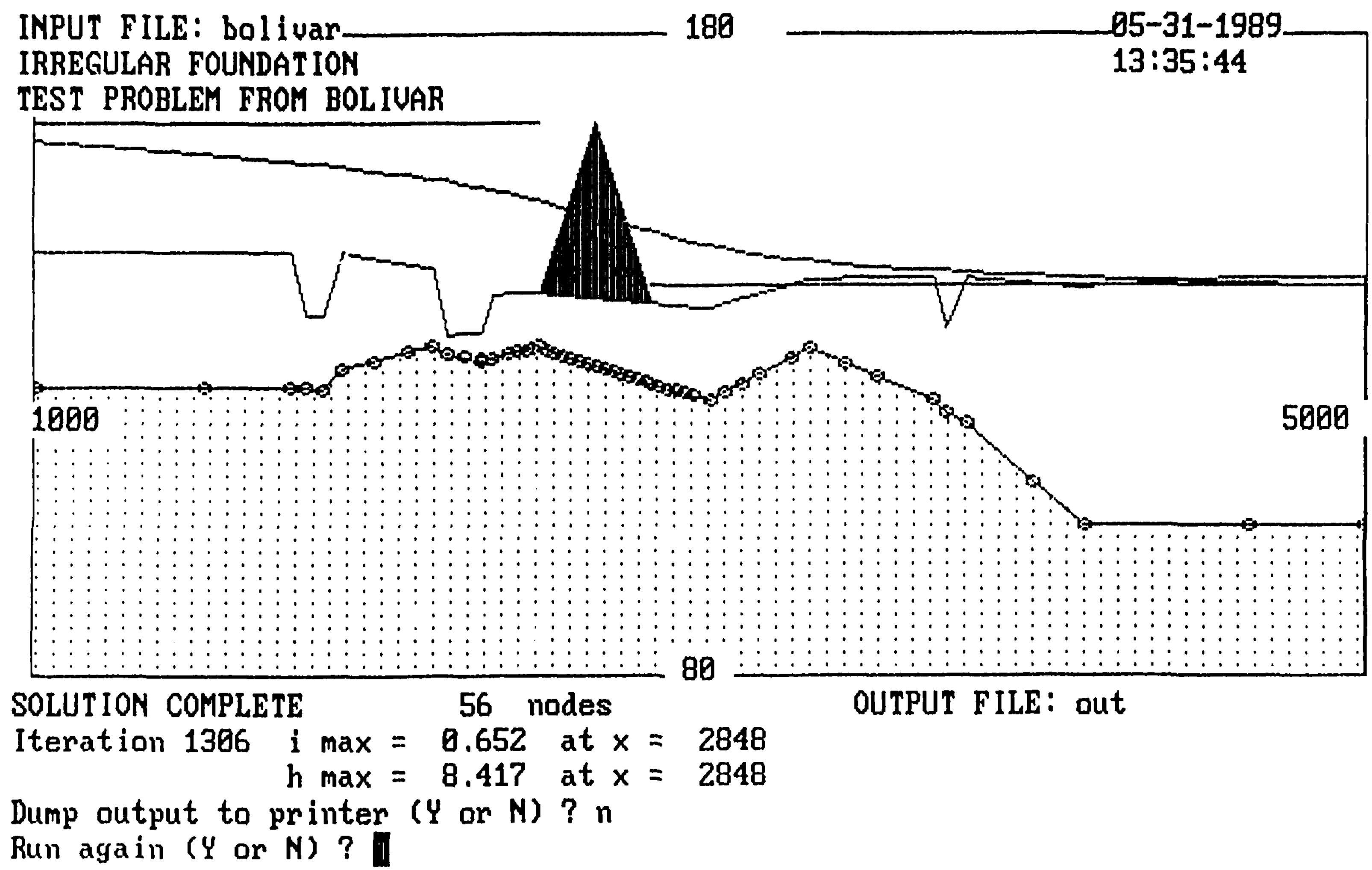


Figure 35. Copy of screen output, Bolivar

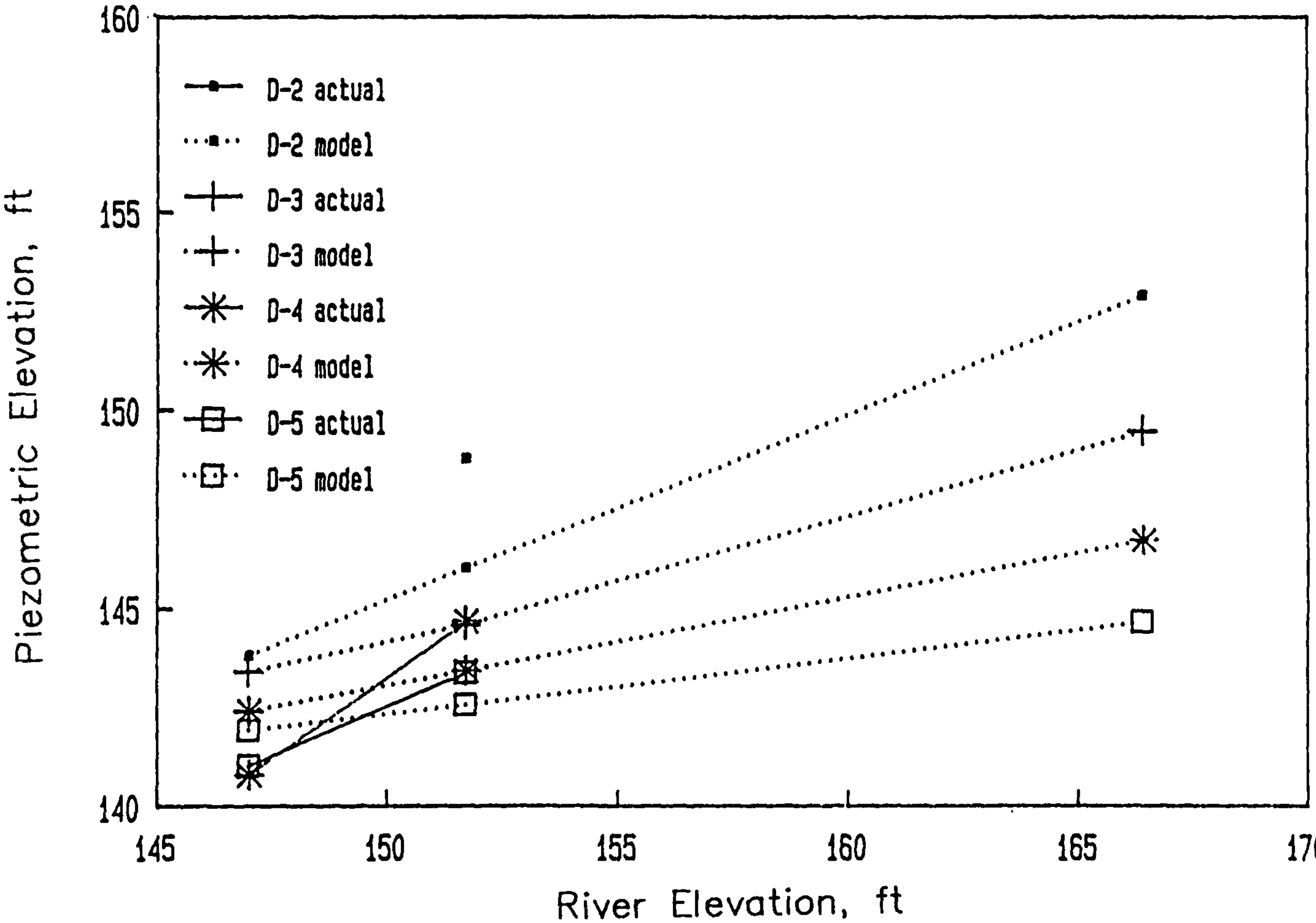


Figure 36. Piezometric elevations versus river elevation, Bolivar

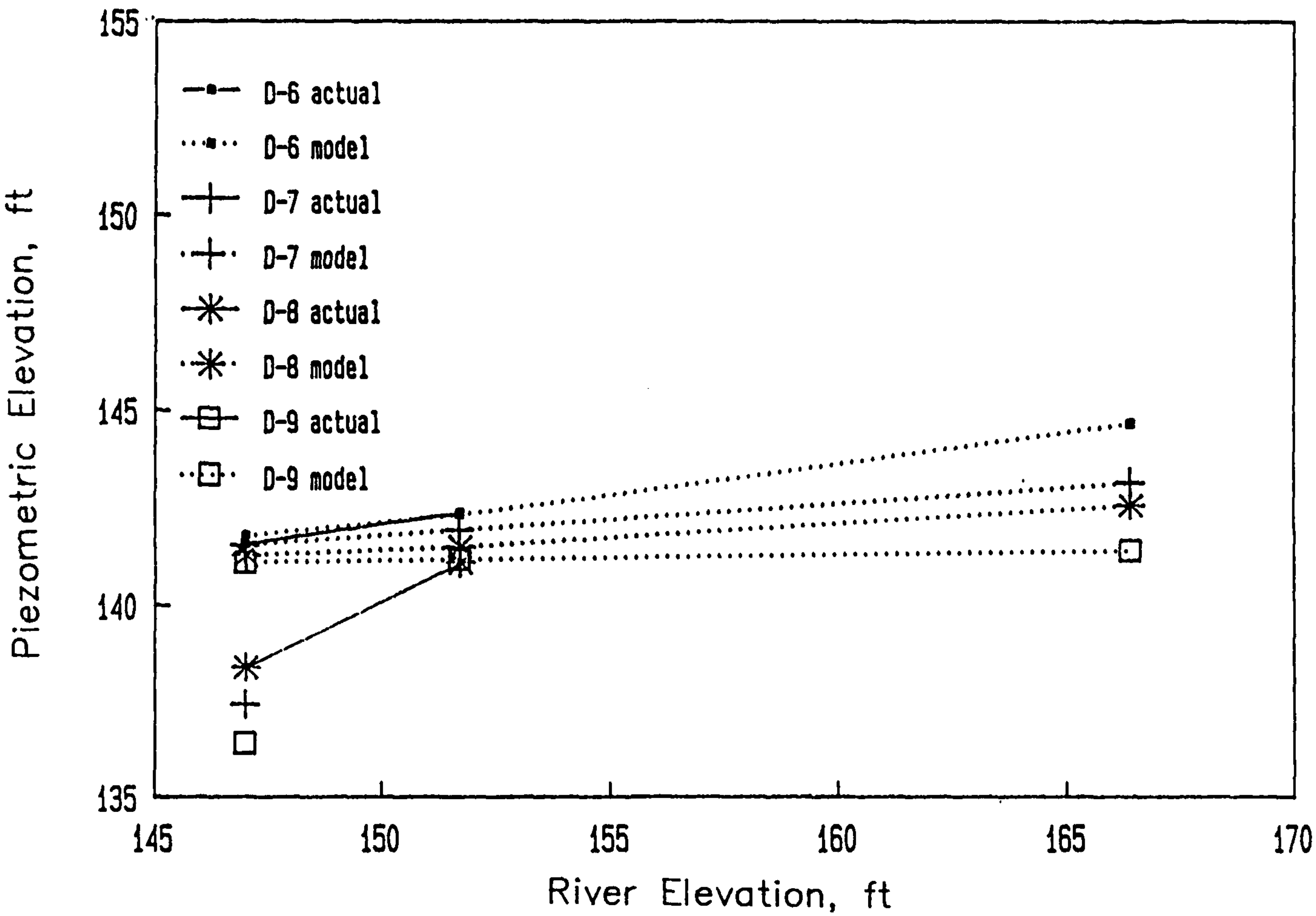


Figure 37. Piezometric elevations versus river elevation, Bolivar

PART V: DESIGN APPLICATIONS

62. Although the program LEVEEMSU was developed primarily as an analysis tool, it can be employed quite readily for preliminary design of underseepage control measures such as seepage berms and relief wells.

Design of Seepage Berms

63. If a semipervious berm is assumed to have a vertical permeability or permeability curve number equal to that of the landside top blanket, a berm can be modeled by adjusting the geometry of the landside blanket to include the berm. By a few trial and error adjustments, a designer can size a berm that will result in any desired gradient at any landside location. Figure 38 illustrates a copy of the screen display for an input file entitled DATABERM. This file was developed by adjusting the geometry of file DATACHK to include a 300-ft-long berm with a thickness of 5 ft at the levee toe and 2 ft at the berm toe. The maximum gradient of 0.71 occurs at the berm toe (x = 2,106). From the printed output file, the gradient at the levee toe and any other location can be obtained. Furthermore, the graphic display of the relationship of the piezometric line to the berm surface provides the designer a clear basis for making trial and error adjustments of berm geometry.

64. A logical improvement to the program would be to automate the berm design process. The program could be given a set of allowable gradient values for different distances from the levee and would automatically adjust the berm surface until the desired gradients were attained.

Design of Relief Wells

65. As previously demonstrated in Part III, use of the option to specify piezometric head at one node allows approximate modeling of a well line and provides the designer with a relationship between average piezometric elevation at the well line and well flow per foot of levee. These results may be sufficient for preliminary studies and cost estimates where only the approximate number of wells is required. Detailed design of a well system including

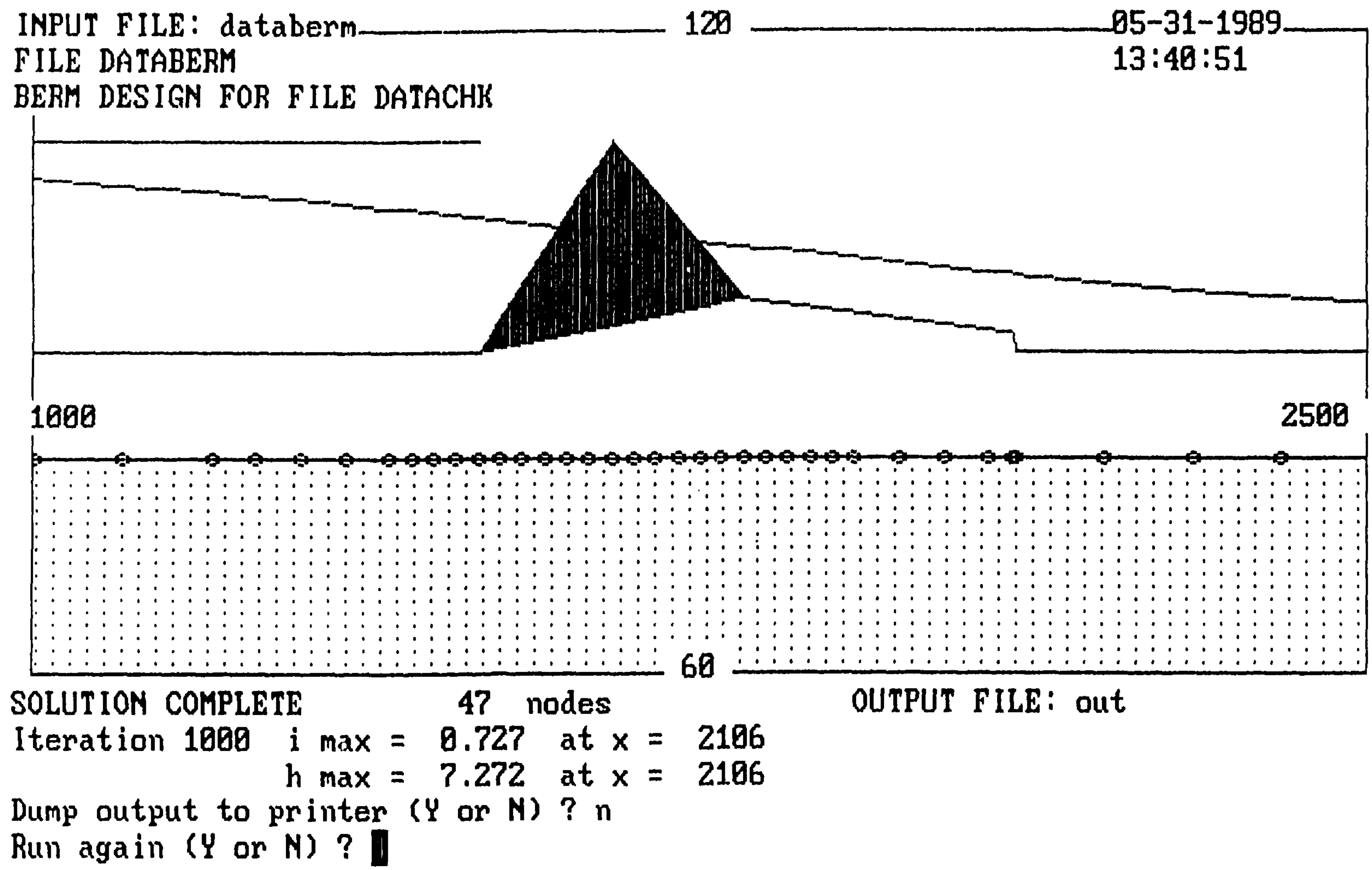


Figure 38. Copy of screen output, file DATABERM

spacing, hydraulic losses, and partial penetration effects is beyond the scope of the present program.

PART VI: SUMMARY, CONCLUSIONS, AND RECOMMENDATIONS

Summary

66. A software package for underseepage analysis of levees, LEVEEMSU, has been developed and tested. The program allows an explicit description of the actual geometry of the top blanket, pervious substratum, and landside water, which need not be regular or uniform. Blanket permeability may be constant or a function of blanket thickness. The residual head and gradient are calculated along the entire length of the top blanket using a finite different approximation of Bennett's equation. A graphic display of the problem and results are provided.

67. A number of parametric studies were performed to test the program and demonstrate it capabilities, which include analysis of levee sections having ditches, borrow pits, sloping ground, and other irregularities. Several prototype reaches were analyzed to assess and demonstrate the program's capability to match observed piezometric conditions along an entire cross section or piezometer range.

Conclusions

68. Although the capabilities of LEVEEMSU would be inherent in a general-purpose finite element program, the development and use of this special-purpose program should have special advantages for levee analysis and design:

a. The program is relatively short and can be run on virtually any IBM compatible microcomputer running the MS DOS (TM) operating system and having CGA or EGA graphics capabilities.

b. The program input and output is specifically oriented to levees. For example, information on the gradient through the top blanket would have to be manually extracted from the output of a general-purpose program.

c. The assumptions made in the analysis are identical to the assumptions inherent in conventional analysis. Thus, program solutions should allow a user to match conventional analyses and then extend them to more complex actual conditions.

69. Based on extensive program testing and parametric studies, a number of conclusions are drawn:

a. The program's algorithm for automatic generation of nodes at variable spacing provides considerably more accurate and consistent solutions than the predecessor program, LEVEEIRR.

b. The program solutions match hand solutions for cases of uniform geometry where companion solutions can be obtained.

c. Parametric studies show that the program exhibits consistent and reasonable behavior with respect to changes in permeability, ground slope, ditch location, relief well characteristics, and other variables.

d. Results of the ground slope study suggest that many observed discrepancies between actual and measured gradients might be attributable to ground slope effects alone.

e. Results of the prototype reach analyses show that field permeability ratios can be estimated by systematically varying program input until a reasonable match to observed conditions is obtained. Using the program, this can be done more precisely than by conventional analysis as the analyst does not need to assign constant "design" values to parameters and dimensions that are in fact variable.

f. LEVEEMSU provides a useful and convenient analysis and design tool that should allow designers to more accurately model actual conditions. Presumably, this should lead to more accurate predictions.

70. Flood protection is a complex system involving design, construction, maintenance, and performance evaluation of levees. An analysis program such as LEVEEMSU can be but one link in such a system. If experience proves that the program provides a capability to more accurately evaluate and predict underseepage conditions, this should lead to a reevaluation of design criteria with a view to both reducing cost and improving safety.

Recommendations

71. Based on the results of this research, the following recommendations are made:

a. The program LEVEEMSU should be field tested by use in District offices and the need for any corrections or improvements assessed.

b. The improvement of LEVEEMSU to provide a design mode should be considered. Given a set of berm design criteria, the program could adjust berm dimensions until the desired gradients are obtained.

c. Development of an extended version of LEVEEMSU to analyze three-layer foundations should be investigated. In many instances, a layer of silty sand or sandy silt between the substratum and top blanket may have significant vertical and horizontal flow components. In such sections, construction of a reasonable analysis model based on two layers is known to be difficult.

d. The need for refining levee design criteria should be assessed. Many current criteria, such as dimensions and location of borrow pits and ditches are necessarily arbitrary and conservative due to the lack of a rational analysis procedure. LEVEEMSU provides the capability for site-specific analysis of such items. Likewise, criteria for sizing seepage berms presumably includes an allowance for discrepancies between the actual ground conditions and the ground conditions analyzed. The use of LEVEEMSU reduces such discrepancies.

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APPENDIX A: DATA INPUT FOR LEVEEMSU

1. Input data are read from a standard ASCII text file which can be created using a word processor or text editor. Information in the input file includes coordinates of the soil profile and information on material properties. Coordinate information is specified in terms of vertical sections cut through the profile. At each specified vertical section, the base of the pervious substratum, base of the top blanket, and ground surface are specified. For landside sections, the landside water surface is also specified. Layer boundaries are assumed to vary linearly between specified sections.

2. An example input file with corresponding variable names and definitions is shown below; a sketch of the corresponding cross section is shown in Figure A-1.

Example Data File:	Variable Names
IRREGULAR FOUNDATION	TITLE1$
TEST PROBLEM	TITLE2$
0.200	KF
2 "CONST" .0002 175	NRIVSECS PERMFLAGR$ PERMRIV YRIV
750.0 60.0 140.0 158.0	X(1), Y1(1), Y2(1), Y3(1)
1750.0 60.0 140.0 160.0	"
4 "CONST" .0002	NLANDSECS PERMFLAGL PERMLAND
1900.0 60.0 140.0 160.0 160.0	X(*), Y1(*), Y2(*), Y3(*), YWATER(*)
2400.0 60.0 120.0 158.33 158.33	"
2800.0 62.0 140.0 155.0 158.33	"
4900.0 70.0 140.0 158.0 158.33	"
NO WELLS	WELLFLAG$

(If it is desired to model the effect of a line of relief well line, the last line above is deleted and two lines are added as shown below)

.

.

WELL	WELLFLAG$
1920 162	XWELL YWELL

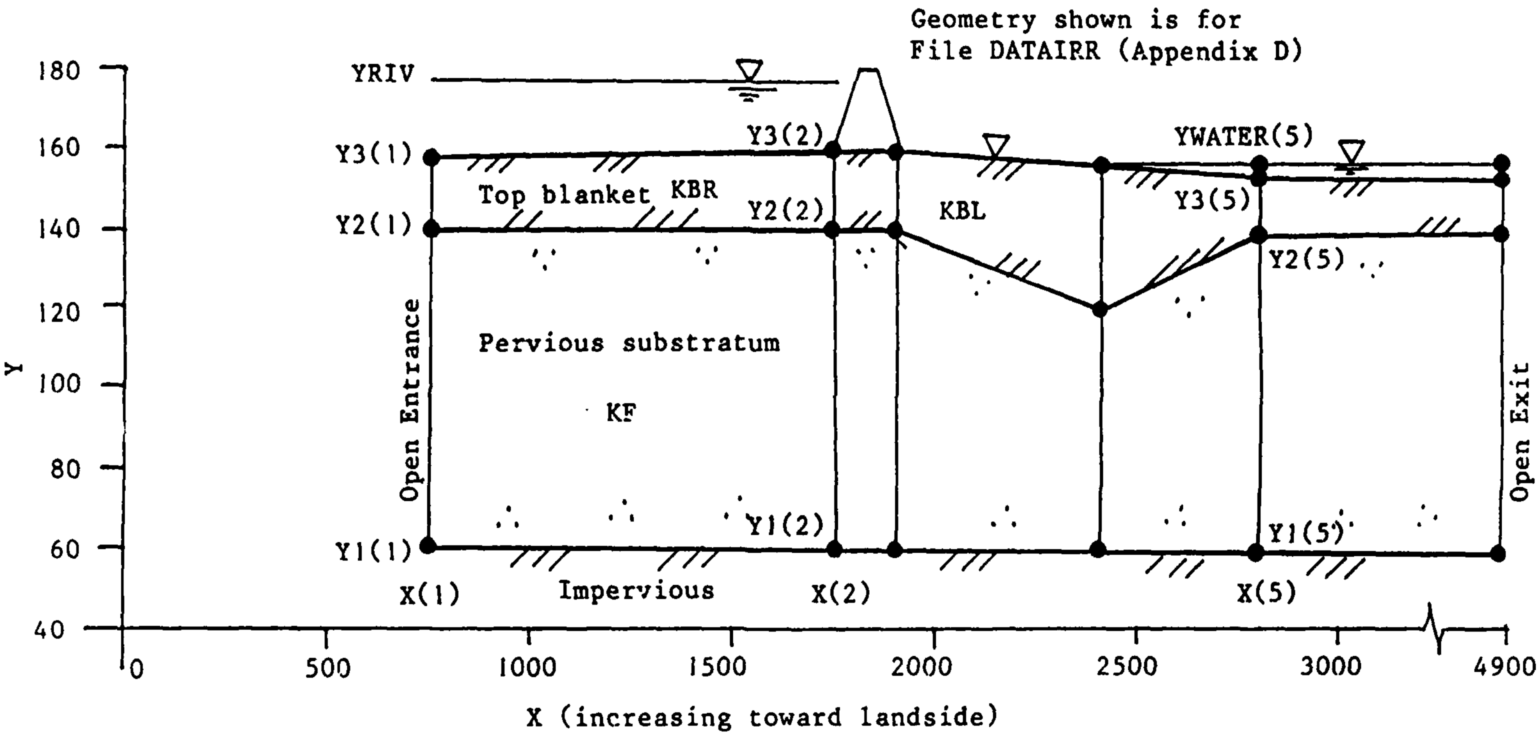


Figure A-1. Definition of input variables.

Definition of Variables

3. Variable definitions are given below in the order they are listed in the sample input file above.

TITLE1$ is the first title line.

TITLE2$ is the second title line (two are required).

KF is the horizontal permeability of the pervious substratum, in ft/min.

NRIVSECS is the number of vertical sections used to describe the problem geometry on the riverside of the levee. NRIVSECS must be two (2) or more. The first section is an open entrance; the last section is the riverside toe of the levee.

PERMFLAGR$ is a flag that indicates how the riverside permeability is to be specified. Use the value "CONST" or "const" to specify a constant riverside blanket permeability. Use the value "CURVE" or "curve" to calculate the riverside blanket permeability as a function of the blanket thickness z .

PERMRIV: If PERMFLAGR$ is "CONST", PERMRIV is the vertical permeability of the riverside top blanket in ft/min. If PERMFLAG$ is "CURVE", PERMRIV is the vertical permeability for a blanket thickness of 10 ft, and the program will calculate the permeability for other thicknesses using the method described in Part II.

YRIV is riverside water elevation.

X(1), Y1(1), Y2(1), Y3(1) are the geometry data for the first vertical section, with x increasing from riverside to landside.

X(1) is the x coordinate
Y1(1) is the base of the pervious substratum
Y2(1) is the top of the pervious substratum/base of the top blanket
Y3(1) is the top of the ground

These lines are repeated for each riverside vertical section. (NRIVSECS lines in all).

NLANDSECS is the number of vertical sections used to describe the problem geometry on the landside of the levee. NLANDSECS must be two (2) or more. The first section is the landside toe of the levee; the last section is an open exit.

PERMFLAGR$ is a flag that indicates how the landside permeability is to be specified. Use the value "CONST" or "const" to specify a constant landside blanket permeability. Use the value "CURVE" or "curve" to calculate the landside blanket permeability as a function of the blanket thickness z .

PERMLAND: If PERMFLAGR$ is "CONST", PERMLAND is the vertical permeability of the landside top blanket in ft/min. If PERMFLAG$ is "CURVE", PERMLAND is the vertical permeability for a blanket thickness of 10 ft, and the program will calculate the permeability for other thicknesses using the method described in Part II.

X(*), Y1(*), Y2(*), Y3(*), YWATER(*) are the geometry data for the first landside vertical section (at the landside toe).

X(*) is the x coordinate
Y1(*) is the base of the pervious substratum
Y2(*) is the top of the pervious substratum/base of the top blanket
Y3(*) is the top of the ground
YWATER(*) is the elevation of the free water surface (typically) equal to or above the ground surface).

These lines are repeated for each landside vertical section. (NLANDSECS lines in all).

WELLFLAG$ is a flag which tells the program to read one additional line giving a specified piezometric elevation at one location, which can be used to simulate a line of relief wells. If a relief well (or specified piezometric head) is to be specified, enter the word WELL or well on this line. If this option is not desired, enter any other word(s), such as NO WELLS, STOP or END.

The following variables are only used if WELLFLAG$ is WELL or well:

XWELL is the x coordinate where the piezometric elevation is to be specified. If a node is not generated at this location, the program will move it to the nearest node. It is recommended that this value be the same as the x coordinate of one of the specified landside sections.

YWELL is the y coordinate of the specified piezometric elevation at XWELL. The piezometric elevation will be forced to the specified value at the specified location. It is equivalent to the average piezometric elevation in a line of wells.

APPENDIX B: RUNNING LEVEEMSU

1. LEVEEMSU.EXE is a stand-alone executable file compiled from a high-level BASIC source code. The program runs on IBM compatible personal computers using the MS DOS operating system and having CGA or EGA graphics capabilities. A math coprocessor is not required, but the program runs considerably faster if a coprocessor is installed. A graphics printer is required to obtain a printer plot of the foundation geometry and results.

2. Before running the program, prepare and save one or more data files in standard ASCII format using a word processor or text editor. Format for data files is given in Appendix A. Any number of files can be analyzed without exiting the program.

3. To obtain a printer plot of a CGA screen display, the DOS command GRAPHICS (program GRAPHICS,.COM) must be resident on the system and executed before running the program. For example (User input is underlined):

C> GRAPHICS

To obtain a printer plot of an EGA screen display from monochrome mode, the public domain program EPSON.COM or a similar EGA screen dump program should be executed before running the program. For example:

C> EPSON

4. To run the program, log to the drive where the program resides (usually drive C:) and type the program name:

C> LEVEEMSU

The program will display introductory information and ask what type of graphics display is available. Respond with:

EGAC or EGAM or CGA

The option EGAC will provide a high resolution color graphic display of the problem. The option EGAM will provide a high resolution monochrome display, suitable for copying to a graphics printer. The option CGA will provide a medium resolution monochrome graphic display of the problem, suitable for copying to a graphics printer.

5. The program will ask for the input file name. Enter the file name. Prefix the file name with the drive identifier and/or path, if different from the default drive and directory. Include the extension if present. For example:

<u>DATAIRR</u>

<u>A:DATAIRR</u>

<u>A:DATAIRR.DAT</u>

are all valid data file identifiers. If the input file specified does not exist, the program will prompt for the file name again.

6. The program will ask for the output file name in a similar fashion. If the named file does not exist, it will be created. If it does exist, it will be overwritten.

7. The program will then ask if you wish to change any of the default settings for closure tolerance, maximum iterations, and maximum node spacing near the levee toe. If you are satisfied with the present settings, press return for each value. If you wish to change these values, type in the new value.

8. The program will print a summary of your input data. If you wish a hard copy, press Shift-PrtSc before pressing Return to continue. Input data are also saved to a specified output file.

9. The program will provide a graphic display of your input data. If you wish a hard copy, press Shift-PrtSc before pressing Return to continue.

10. The program will then solve for the head and gradient along the base of the blanket. When the solution is complete, it will plot the piezometric grade line. If you wish a hard copy, press Shift-PrtSc before pressing Return to continue.

11. The program will ask whether the graphics window is to be changed. This feature allows zooming in on a particular area of interest. Enter Y(es) or N(o) . If the response is yes, the program will display the coordinates of the current window and prompt you for the new window coordinates. These are entered as minimum and maximum x and y values, respectively, separated by commas. The window boundaries can be changed as often as desired.

12. The program will ask whether the results are to be listed to the printer. Enter Y(es) or N(o) . Whether printed or not, results are saved in the output file for later printing using a word processor or the DOS COPY or PRINT commands.

13. The program will then prompt for a new problem. Enter Y(es) to go to a new problem, or N(o) to quit.

APPENDIX C: EXAMPLE RUN, FILE DATACHK

```
         --- LEVEEMSU ---
     UNDERSEEPAGE ANALYSIS
              FOR
 IRREGULAR FOUNDATION CONDITIONS

        Thomas F. Wolff
   Michigan State University


       U. S. Army Engineer
  Waterways Experiment Station
    Geotechnical Laboratory


Last revision  May 31, 1989


Enter graphics mode
EGAC for Hi Res color
EGAM for Hi Res monochrome
CGA for Med Res monochrome
? egac






 ENTER INPUT FILE NAME
 ? datachk

 ENTER OUTPUT FILE NAME
 ? out
```

```
DEFAULT SETTINGS
Press return if OK
Type new number to change

Tolerance =  .0005
?
Maximum iterations =  1000
?
Maximum node spacing near levee =  25
?
```

```
Data file: datachk

IRREGULAR FOUNDATION
TEST PROBLEM

Foundation Permeability
 .2

Riverside
sections        permflag      perm        yriv
 2              CONST         .0002       110
 x              y1            y2          y3
 0              0             80          90
 1500           0             80          90

Landside
sections        permflag      perm
 2              CONST         .0002
 x              y1            y2          y3          ywater
 1800           0             80          90          90
 5000           0             80          90          90

Press Return to Continue
?
```

Listed Output File

```
PROGRAM LEVEEMSU  May 31, 1989 edition
INPUT FILE: datachk
OUTPUT FILE: out

IRREGULAR FOUNDATION
TEST PROBLEM

KF =  .2
PERMFLAGR = CONST    PERMRIV  =  .0002
PERMFLAGL = CONST    PERMLAND =  .0002
```

xx	yy1	yy2	yy3	yywater	d	z	kb
0.00	0.00	80.00	90.00	110.00	80.0	10.0	0.20000E-03
500.00	0.00	80.00	90.00	110.00	80.0	10.0	0.20000E-03
700.00	0.00	80.00	90.00	110.00	80.0	10.0	0.20000E-03
900.00	0.00	80.00	90.00	110.00	80.0	10.0	0.20000E-03
1000.00	0.00	80.00	90.00	110.00	80.0	10.0	0.20000E-03
1100.00	0.00	80.00	90.00	110.00	80.0	10.0	0.20000E-03
1200.00	0.00	80.00	90.00	110.00	80.0	10.0	0.20000E-03
1250.00	0.00	80.00	90.00	110.00	80.0	10.0	0.20000E-03
1300.00	0.00	80.00	90.00	110.00	80.0	10.0	0.20000E-03
1350.00	0.00	80.00	90.00	110.00	80.0	10.0	0.20000E-03
1400.00	0.00	80.00	90.00	110.00	80.0	10.0	0.20000E-03
1425.00	0.00	80.00	90.00	110.00	80.0	10.0	0.20000E-03
1450.00	0.00	80.00	90.00	110.00	80.0	10.0	0.20000E-03
1475.00	0.00	80.00	90.00	110.00	80.0	10.0	0.20000E-03
1500.00	0.00	80.00	90.00	110.00	80.0	10.0	0.20000E-03
1525.00	0.00	80.00	90.00	108.33	80.0	10.0	0.00000E+00
1550.00	0.00	80.00	90.00	106.67	80.0	10.0	0.00000E+00
1575.00	0.00	80.00	90.00	105.00	80.0	10.0	0.00000E+00
1600.00	0.00	80.00	90.00	103.33	80.0	10.0	0.00000E+00
1625.00	0.00	80.00	90.00	101.67	80.0	10.0	0.00000E+00
1650.00	0.00	80.00	90.00	100.00	80.0	10.0	0.00000E+00
1675.00	0.00	80.00	90.00	98.33	80.0	10.0	0.00000E+00
1700.00	0.00	80.00	90.00	96.67	80.0	10.0	0.00000E+00
1725.00	0.00	80.00	90.00	95.00	80.0	10.0	0.00000E+00
1750.00	0.00	80.00	90.00	93.33	80.0	10.0	0.00000E+00
1775.00	0.00	80.00	90.00	91.67	80.0	10.0	0.00000E+00
1800.00	0.00	80.00	90.00	90.00	80.0	10.0	0.20000E-03
1825.00	0.00	80.00	90.00	90.00	80.0	10.0	0.20000E-03
1850.00	0.00	80.00	90.00	90.00	80.0	10.0	0.20000E-03
1875.00	0.00	80.00	90.00	90.00	80.0	10.0	0.20000E-03
1900.00	0.00	80.00	90.00	90.00	80.0	10.0	0.20000E-03
1925.00	0.00	80.00	90.00	90.00	80.0	10.0	0.20000E-03
1975.00	0.00	80.00	90.00	90.00	80.0	10.0	0.20000E-03
2025.00	0.00	80.00	90.00	90.00	80.0	10.0	0.20000E-03
2075.00	0.00	80.00	90.00	90.00	80.0	10.0	0.20000E-03

2125.00	0.00	80.00	90.00	90.00	80.0	10.0	0.20000E-03
2225.00	0.00	80.00	90.00	90.00	80.0	10.0	0.20000E-03
2325.00	0.00	80.00	90.00	90.00	80.0	10.0	0.20000E-03
2425.00	0.00	80.00	90.00	90.00	80.0	10.0	0.20000E-03
2625.00	0.00	80.00	90.00	90.00	80.0	10.0	0.20000E-03
2825.00	0.00	80.00	90.00	90.00	80.0	10.0	0.20000E-03
3325.00	0.00	80.00	90.00	90.00	80.0	10.0	0.20000E-03
3825.00	0.00	80.00	90.00	90.00	80.0	10.0	0.20000E-03
4325.00	0.00	80.00	90.00	90.00	80.0	10.0	0.20000E-03
4825.00	0.00	80.00	90.00	90.00	80.0	10.0	0.20000E-03
5000.00	0.00	80.00	90.00	90.00	80.0	10.0	0.20000E-03

xx	piezel	reshead	z	i
0.00	110.00	0.00	10.00	0.000
500.00	108.33	-1.67	10.00	-0.167
700.00	107.41	-2.59	10.00	-0.259
900.00	106.36	-3.64	10.00	-0.364
1000.00	105.77	-4.23	10.00	-0.423
1100.00	105.12	-4.88	10.00	-0.488
1200.00	104.42	-5.58	10.00	-0.558
1250.00	104.04	-5.96	10.00	-0.596
1300.00	103.64	-6.36	10.00	-0.636
1350.00	103.23	-6.77	10.00	-0.677
1400.00	102.79	-7.21	10.00	-0.721
1425.00	102.56	-7.44	10.00	-0.744
1450.00	102.33	-7.67	10.00	-0.767
1475.00	102.09	-7.91	10.00	-0.791
1500.00	101.84	-8.16	10.00	-0.816
1525.00	101.60	-6.74	10.00	-0.674
1550.00	101.35	-5.32	10.00	-0.532
1575.00	101.10	-3.90	10.00	-0.390
1600.00	100.85	-2.48	10.00	-0.248
1625.00	100.60	-1.06	10.00	-0.106
1650.00	100.36	0.36	10.00	0.036
1675.00	100.11	1.78	10.00	0.178
1700.00	99.86	3.19	10.00	0.319
1725.00	99.61	4.61	10.00	0.461
1750.00	99.37	6.03	10.00	0.603
1775.00	99.12	7.45	10.00	0.745
1800.00	98.87	8.87	10.00	0.887
1825.00	98.62	8.62	10.00	0.862
1850.00	98.39	8.39	10.00	0.839
1875.00	98.15	8.15	10.00	0.815
1900.00	97.93	7.93	10.00	0.793
1925.00	97.71	7.71	10.00	0.771
1975.00	97.29	7.29	10.00	0.729
2025.00	96.89	6.89	10.00	0.689
2075.00	96.51	6.51	10.00	0.651

2125.00	96.15	6.15	10.00	0.615
2225.00	95.49	5.49	10.00	0.549
2325.00	94.90	4.90	10.00	0.490
2425.00	94.37	4.37	10.00	0.437
2625.00	93.48	3.48	10.00	0.348
2825.00	92.76	2.76	10.00	0.276
3325.00	91.56	1.56	10.00	0.156
3825.00	90.85	0.85	10.00	0.085
4325.00	90.41	0.41	10.00	0.041
4825.00	90.10	0.10	10.00	0.010
5000.00	90.00	0.00	10.00	0.000

APPENDIX D: EXAMPLE DATA FILES

1. Following are listings of "standard" data files used as the basis of parametric studies in Part III of the report. Working from these files, the parametric studies were performed by systematically altering the input file. Copies of screen display illustrating the geometry are shown in Part III of this report.

2. DATACHK models a levee section amenable to conventional analysis. It has a 10-ft-thick top blanket overlying an 80-ft-thick pervious substratum. An example is listed below:

```
IRREGULAR FOUNDATION
TEST PROBLEM
.2000
2 "CONST" .0002 110
0 0 80 90
1550 0 80 90
2 "CONST" .0002
1800 0 80 90 90
5000 0 80 90 90
NO WELL
```

3. File DATAIRR models an irregular top blanket having a thick clay plug paralleling the levee. An example of such is listed below:

```
IRREGULAR FOUNDATION
TEST PROBLEM
0.200
2 "CONST" .0002 175
750.0 60.0 140.0 158.0
1750.0 60.0 140.0 160.0
4 "CONST" .0002
1900.0 60.0 140.0 160.0 160.0
2400.0 60.0 120.0 158.33 158.33
2800.0 62.0 140.0 155.0 158.33
```

```
4900.0 70.0 140.0 158.0 158.33
NO WELLS
```

4. File DATADCH models a levee section with a 15-ft-thick top blanket and a landside ditch. It is listed below:

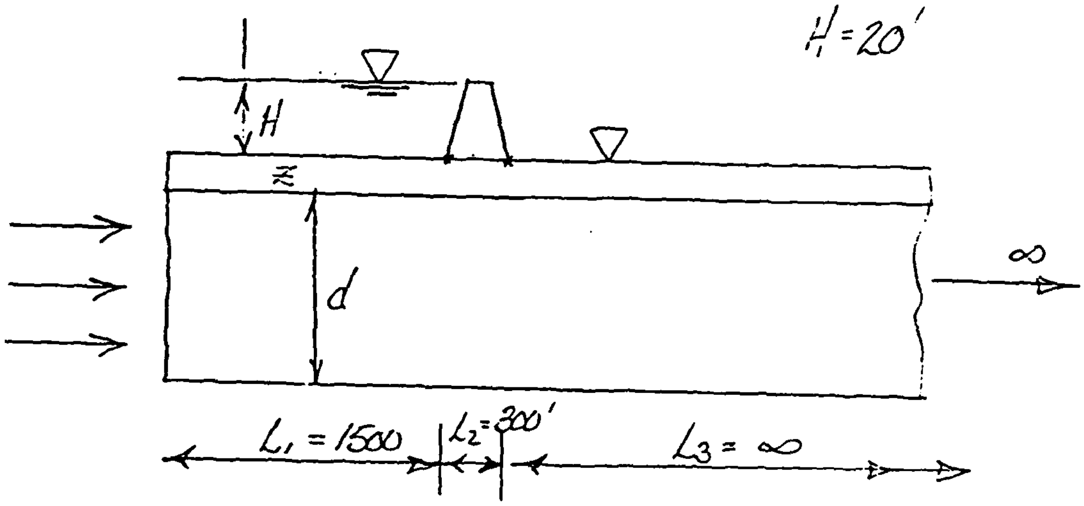
```
TEST FILE "DATADCH"
DITCH 1V ON 3H  200 FT FROM LEVEE  10 FT DEEP
200
2 "CONST" .0003 100
0 0 65 80
2000 0 65 80
6 "CONST" .0003
2200 0 65 80 80
2400 0 65 80 80
2430 0 65 70 80
2440 0 65 70 80
2470 0 65 80 80
7000 0 65 80 80
NO WELLS
```

5. File DATAWELL is similar to file DATACHK with the exception that a line of relief wells is molded at the levee toe. It is also listed below:

```
IRREGULAR FOUNDATION
TEST PROBLEM
0.2000
2 "CONST" 0.0002 110
0 0 80 90
1500 0 80 90
2 "CONST" 0.0002
1800 0 80 90 90
5000 0 80 90 90
WELL
1820 94
```

Hand check for data file DATACHK

$H_1' = 20'$



$H_1' = 20'$ $\qquad L_1 = 1500'$ $\qquad k_f/k_t = 1000$

$z = 10'$ $\qquad L_2 = 300'$

$d = 80$ $\qquad L_3 = \infty$

$$c_r = \sqrt{\frac{k_{br}}{k_f \cdot z \cdot d}} = \sqrt{\frac{(1)}{1000 \cdot 10 \cdot 80}} = 0.001118033$$

same for riverside and landside

$$x_3 = \frac{1}{c} = 894.43'$$

$$x_1 = \frac{\tanh(cL_1)}{c} = \frac{\tanh(.001118033 \times 1500)}{0.001118033}$$

$$x_1 = 834.03'$$

$$h_o = \frac{H x_3}{x_1 + L_2 + x_3} = \frac{(20)(894.43)}{834.03 + 300 + 894.43} = \boxed{8.819'}$$

Rework using open exit @ $L_3 = 3000'$ (modeled problem).

$$x_3 = \frac{\tanh(c \cdot L_3)}{c} = \frac{\tanh(.001118033 \times 3000)}{.001118033} = 892.25$$

$$h_o = \frac{(20)(892.25)}{834.03 + 300 + 894.03} = \boxed{8.799}$$

Calculated gradient: ($z = 10'$)

Theoretical problem	0.882
Modeled problem	0.880

Landside Heads: ($L_3 = \infty$)

x computer	x landside	$h_x = h_o e^{-cx}$	Computer
1800	0	8.819'	8.862
2000	200	7.052	7.075
2200	400	5.639	
2400	600	4.509	
2600	800	3.606	
2800	1000	2.883	
3000	1200	2.305	

1800	0	8.819'	8.862
2000	200	7.052'	7.075
2250	450	5.332	5.332
2450	650	4.264	4.245
2700	900	3.048	3.193
2950	1150	2.438	2.391
3450	1650	1.394	1.346
3950	2150	.797	.723
4450	2650	.456	.325

Landside Heads ($L_3 = 3000$)

$$h_x = h_0 \frac{\sinh c(L_3 - x)}{\sinh cL_3} = \frac{8.819 \sinh[.001118033(3000-x)]}{\sinh(.001118033 \times 3000)}$$

$$= 0.6170398 \sinh[.001118033(3000-x)]$$

x computer	x landside	h_x
1800	0	8.819 ✓
2000	200	7.047
2250	450	5.321
2450	650	4.247
2700	900	3.199
2950	1150	2.402
3450	1650	1.327
3950	2150	.679
4450	2650	.243

APPENDIX F: PROGRAM LISTING

```
' -----------------------------------------
'              PROGRAM LEVEEMSU            '
'                                          '
'         LEVEE UNDERSEEPAGE ANALYSIS      '
'                    FOR                   '
'       IRREGULAR FOUNDATION CONDITIONS    '
'                                          '
'         Thomas F. Wolff, Ph.D., P.E.     '
'          Michigan State University       '
'                  May 1989                '
'             Last revision 6/1/89         '
' ---------------------------------------- '

' *** START ***
start:
CLEAR

'-- set dimensions ---
REM $STATIC
DIM x(40), y1(40), y2(40), y3(40), ywater(40)
DIM xx(200), yy1(200), yy2(200), yy3(200), yywater(200)
DIM d(200), z(200), kb(200), piezel(200), oldpzel(200)
DIM c1(200), c2(200), c3(200)
DIM reshead(200), iexit(200)

' --- define format strings ---
FormStr1$ = "Iteration ####  i max = ##.###  at x = #####"
FormStr2$ = "                h max = ##.###  at x = #####"
FormStr3$ = "#####.## ####.## ####.## ####.## ####.## ###.# ###.# #.#####^^^^"
FormStr4$ = "#####.## ####.## ####.## ####.## ###.### "
blank40$ = "                                        "

'--- set changedate ---
changedate$ = " May 31, 1989"

' --- set defaults and initialize variables ---
dx = 25
maxiters% = 1000
tol = .0005
well% = 0
```

```
' *** OPENING SCREEN ***

' --- print banner ---
SCREEN 0
CLS
COLOR 15, 2
PRINT "        --- LEVEEMSU ---          "
PRINT "     UNDERSEEPAGE ANALYSIS        "
PRINT "              FOR                 "
PRINT " IRREGULAR FOUNDATION CONDITIONS "
PRINT
PRINT "         Thomas F. Wolff          "
PRINT "   Michigan State University      "

PRINT
COLOR 15, 4
PRINT
PRINT "      U. S. Army Engineer         "
PRINT "  Waterways Experiment Station    "
PRINT "    Geotechnical Laboratory       "
PRINT
PRINT
PRINT "Last revision "; changedate$

GOSUB msuflag
GOSUB corpsflag

'--- set graphics chip ---
COLOR 15, 2
LOCATE 17, 1
setchip:

PRINT
PRINT "Enter graphics mode"
PRINT "EGAC for Hi Res color"
PRINT "EGAM for Hi Res monochrome"
PRINT "CGA for Med Res monochrome"

INPUT chip$

IF chip$ = "EGAC" OR chip$ = "egac" THEN
   chip$ = "egac"
   sandcolor = 8
   claycolor = 6
   leveecolor = 4
   watercolor = 3
```

```
ELSEIF chip$ = "EGAM" OR chip$ = "egam" THEN
   chip$ = "egam"
   Row1$ = CHR$(0) + CHR$(0) + CHR$(0) + CHR$(0)
   Row2$ = CHR$(0) + CHR$(0) + CHR$(0) + CHR$(0)
   Row3$ = CHR$(16) + CHR$(16) + CHR$(16) + CHR$(0)
   Row4$ = CHR$(0) + CHR$(0) + CHR$(0) + CHR$(0)
   Row5$ = CHR$(0) + CHR$(0) + CHR$(0) + CHR$(0)
   sandtile$ = Row1$ + Row2$ + Row3$ + Row4$ + Row5$
   sandcolor = 7
   claycolor = 7
   leveecolor = 7
   watercolor = 7
ELSEIF chip$ = "CGA" OR chip$ = "cga" THEN
   chip$ = "cga"
   sandcolor = 1
   sandtile$ = CHR$(0) + CHR$(0) + CHR$(16) + CHR$(0) + CHR$(0)
   claycolor = 1
   leveecolor = 1
   watercolor = 1
ELSE
   GOTO setchip
END IF


    ' *** SECOND SCREEN - INPUT ***
    getinfilename:
    COLOR 7, 1
    CLS
    PRINT
    COLOR 10, 1
    PRINT "ENTER INPUT FILE NAME"
    COLOR 7, 1
    ON ERROR GOTO getinfilename
    INPUT infile$
    OPEN infile$ FOR INPUT AS #1
    CLOSE 1

    getoutfilename:
    ON ERROR GOTO getoutfilename
    PRINT
    COLOR 10, 1
    PRINT "ENTER OUTPUT FILE NAME"
    COLOR 7, 1
    INPUT outfile$
    IF (outfile$ = infile$) THEN
       COLOR 10, 1
       PRINT "MUST BE DIFFERENT THAN INPUT FILE"
       GOTO getoutfilename
    END IF
```

```
' *** THIRD SCREEN -- DEFAULTS ***
defaults:
COLOR 7, 1
CLS
COLOR 10, 1
PRINT "DEFAULT SETTINGS"
COLOR 7, 1
PRINT "Press return if OK"
PRINT "Type new number to change"
PRINT

point1:
ON ERROR GOTO point1
PRINT "Tolerance = "; tol
INPUT value
IF value > 0 THEN
   tol = value
   COLOR 10, 1
   GOTO point1
END IF
COLOR 7, 1

point2:
ON ERROR GOTO point2
PRINT "Maximum iterations = "; maxiters%
INPUT value
IF value > 0 THEN

   maxiters% = value
   COLOR 10, 1
   GOTO point2
END IF
COLOR 7, 1

point3:
ON ERROR GOTO point3
PRINT "Maximum node spacing near levee = "; dx
INPUT value
IF value > 0 THEN
   dx = value
   COLOR 10, 1
   GOTO point3
END IF
```

```
' *** *** INPUT FROM FILE *** ***
readdata:
ON ERROR GOTO infileerror
OPEN infile$ FOR INPUT AS #1
INPUT #1, title1$
INPUT #1, title2$
INPUT #1, kf
INPUT #1, nrivsecs%, permflagr$, permriv, yriv
FOR j% = 1 TO nrivsecs%
   INPUT #1, x(j%), y1(j%), y2(j%), y3(j%)
   ywater(j%) = yriv
NEXT j%

INPUT #1, nlandsecs%, permflagl$, permland
nsecs% = nrivsecs% + nlandsecs%

FOR j% = nrivsecs% + 1 TO nsecs%
   INPUT #1, x(j%), y1(j%), y2(j%), y3(j%), ywater(j%)
NEXT j%
INPUT #1, wellflag$
IF wellflag$ = "well" OR wellflag$ = "WELL" THEN
   INPUT #1, xwell, ywell
   well% = 1
END IF
CLOSE 1

'--- disble error handler ---
ON ERROR GOTO 0

' *** FOURTH SCREEN -- DISPLAY INPUT ****
listfile:
COLOR 7, 1
CLS
COLOR 10, 1
PRINT "Data file: ";
COLOR 7, 1
PRINT infile$
PRINT
```

```
PRINT title1$
PRINT title2$
PRINT
COLOR 10, 1
PRINT "Foundation Permeability"
COLOR 7, 1
PRINT kf
PRINT
COLOR 10, 1
PRINT "Riverside"
PRINT "sections     permflag     perm        yriv"
COLOR 7, 1
PRINT nrivsecs%, permflagr$, permriv, yriv
COLOR 10, 1
PRINT " x            y1           y2          y3    "
COLOR 7, 1
FOR j% = 1 TO nrivsecs%
   IF CSRLIN > 23 THEN
      COLOR 10, 1
      INPUT "Press return to continue"; code$
      CLS
      COLOR 7, 1
   END IF
   PRINT x(j%), y1(j%), y2(j%), y3(j%)
NEXT j%
PRINT
   IF CSRLIN > 23 THEN
      COLOR 10, 1
      INPUT "Press return to continue"; code$
      CLS
      COLOR 7, 1
   END IF
COLOR 10, 1
PRINT "Landside"
PRINT "sections     permflag     perm"
COLOR 7, 1
PRINT nlandsecs%, permflagl$, permland
COLOR 10, 1
PRINT " x            y1           y2          y3          ywater"
COLOR 7, 1
COLOR 7, 1
FOR j% = nrivsecs% + 1 TO nsecs%
   IF CSRLIN > 23 THEN
      COLOR 10, 1
      INPUT "Press return to continue"; code$
      CLS
      COLOR 7, 1
   END IF
   PRINT x(j%), y1(j%), y2(j%), y3(j%), ywater(j%)
NEXT j%
```

```
IF well% = 1 THEN
   PRINT
   IF CSRLIN > 23 THEN
      COLOR 10, 1

         INPUT "Press return to continue"; code$
         CLS
         COLOR 7, 1
      END IF
      PRINT "XWELL", "YWELL"
      PRINT xwell, ywell
   END IF
   PRINT
   COLOR 10, 1
   PRINT "Press Return to Continue"
   INPUT code$

   ' --- FIFTH SCREEN --START GRAPHICS ---
   CLS
   IF chip$ = "egac" THEN
      SCREEN 9
      VIEW (10, 10)-(630, 260), , 8
   ELSEIF chip$ = "egam" THEN
      SCREEN 9
      VIEW (10, 10)-(630, 260), , 7
   ELSE
      SCREEN 2
      VIEW (10, 10)-(630, 150), , 1
   END IF

   '--- define initial window ---
   xwmin = x(1) - 100
   xwmax = x(nsecs%) + 100
   ywmin = y1(1) - 40
   ywmax = y3(nsecs%) + 50
   WINDOW (xwmin, ywmin)-(xwmax, ywmax)

   GOSUB drawsection
   GOSUB displaytitles


   '--- pause for copy ---
   LOCATE 20, 1
   PRINT "Press return to continue
   INPUT ; code$

   ' $$$ $$$ ANALYSIS $$$ $$$
```

```
' --- generate nodes ---
LOCATE 20, 1
PRINT "Generating Nodes
i% = 0
j% = 0

NewSegment:
i% = i% + 1
j% = j% + 1
xx(j%) = x(i%)
yy1(j%) = y1(i%)

 yy2(j%) = y2(i%)
 yy3(j%) = y3(i%)
 yywater(j%) = ywater(i%)
 d(j%) = yy2(j%) - yy1(j%)
 z(j%) = yy3(j%) - yy2(j%)
 IF i% < nrivsecs% THEN
    kb(j%) = permriv
 ELSEIF i% = nrivsecs% THEN
    kb(j%) = permriv
    jrtoe% = j%
 ELSEIF i% = nrivsecs% + 1 THEN
    kb(j%) = permland
    jltoe% = j%
 ELSEIF i% > nrivsecs% + 1 THEN
    kb(j%) = permland
 END IF

 ' --- calculate slopes for node interpolation ---
 denom = (x(i% + 1) - x(i%))
 slope1 = (y1(i% + 1) - y1(i%)) / denom
 slope2 = (y2(i% + 1) - y2(i%)) / denom
 slope3 = (y3(i% + 1) - y3(i%)) / denom
 slopewater = (ywater(i% + 1) - ywater(i%)) / denom

 NewNode:
 j% = j% + 1
 ' ---  shorten node spacing near levee ---
 IF xx(j% - 1) < x(nrivsecs%) - 1000 THEN
    dxx = dx * 20
 ELSEIF xx(j% - 1) < x(nrivsecs%) - 600 THEN
    dxx = dx * 8
 ELSEIF xx(j% - 1) < x(nrivsecs%) - 300 THEN
    dxx = dx * 4
 ELSEIF xx(j% - 1) < x(nrivsecs%) - 100 THEN
    dxx = dx * 2
 ELSEIF xx(j% - 1) > x(nrivsecs% + 1) + 1000 THEN
    dxx = dx * 20
 ELSEIF xx(j% - 1) > x(nrivsecs% + 1) + 600 THEN
    dxx = dx * 8
```

```
ELSEIF xx(j% - 1) > x(nrivsecs% + 1) + 300 THEN
   dxx = dx * 4
ELSEIF xx(j% - 1) > x(nrivsecs% + 1) + 100 THEN
   dxx = dx * 2
ELSE dxx = dx
END IF
xx(j%) = xx(j% - 1) + dxx
IF j% > 200 THEN
   PRINT "too many nodes"
   STOP
ELSEIF xx(j%) >= x(nsecs%) THEN
   GOTO StopNodes
ELSEIF xx(j%) >= x(i% + 1) THEN
   j% = j% - 1
   GOTO NewSegment

    END IF
    yy1(j%) = yy1(j% - 1) + slope1 * dxx
    yy2(j%) = yy2(j% - 1) + slope2 * dxx
    yy3(j%) = yy3(j% - 1) + slope3 * dxx
    yywater(j%) = yywater(j% - 1) + slopewater * dxx
    d(j%) = yy2(j%) - yy1(j%)
    z(j%) = yy3(j%) - yy2(j%)
    kb(j%) = kb(j% - 1)
    GOTO NewNode

    StopNodes:
    nnodes% = j%
    xx(j%) = x(nsecs%)
    yy1(j%) = y1(nsecs%)
    yy2(j%) = y2(nsecs%)
    yy3(j%) = y3(nsecs%)
    yywater(j%) = ywater(nsecs%)
    d(j%) = yy2(j%) - yy1(j%)
    z(j%) = yy3(j%) - yy2(j%)
    kb(j%) = kb(j% - 1)
    LOCATE 20, 26
    PRINT nnodes%; " nodes "
    GOSUB graphnodes

    '--- zero blanket permeabilities under levee ---
    FOR j% = jrtoe% + 1 TO jltoe% - 1
       kb(j%) = 0
    NEXT j%

    '--- adjust variable permeabilities ---
    IF (permflagr$ = "curve") OR (permflagr$ = "CURVE") THEN
       FOR j% = 1 TO jrtoe%
          kb(j%) = permriv / (EXP(-.065924 * (10 - z(j%))))
       NEXT j%
    END IF
```

```
IF (permflagl$ = "curve") OR (permflagl$ = "CURVE") THEN
   FOR j% = jltoe% TO nnodes%
      kb(j%) = permland / (EXP(-.065924 * (10 - z(j%))))
   NEXT j%
END IF

' *** PRINT NODE INFO TO OUTPUT FILE ***
OPEN outfile$ FOR OUTPUT AS #2
PRINT #2, "PROGRAM LEVEEMSU "; changedate$; " edition"
PRINT #2, "INPUT FILE: "; infile$
PRINT #2, "OUTPUT FILE: "; outfile$
PRINT #2,
PRINT #2, title1$
PRINT #2, title2$
PRINT #2,
PRINT #2, "KF = "; kf
PRINT #2, "PERMFLAGR = "; permflagr$; "    PERMRIV  = "; permriv
PRINT #2, "PERMFLAGL = "; permflagl$; "    PERMLAND = "; permland
IF well% = 1 THEN
   PRINT #2,
   PRINT #2, "WELL LINE AT X   = "; xwell
   PRINT #2, "AVGERAGE PIEZ EL = "; ywell
END IF
PRINT #2,
PRINT #2, "      xx      yy1     yy2     yy3 yywater     d      z          kb"
PRINT #2,
FOR j% = 1 TO nnodes%
PRINT #2, USING FormStr3$; xx(j%); yy1(j%); yy2(j%); yy3(j%); yywater(j%); d(j%); z(j%); kb(j%)
NEXT j%

'--- FIND WELL NODE IF PRESENT ---
IF well% = 1 THEN
   FOR j% = jltoe% TO nnodes%
      IF (xwell > xx(j% - 1)) AND (xwell < xx(j% + 1)) THEN
      jwell% = j%
      END IF
   NEXT j%
END IF

'--- INITIALIZE PIEZOMETRIC ELEVATIONS ---'
LOCATE 20, 1
PRINT "Initializing       "
x1 = SQR((kf / kb(jrtoe% - 1)) * z(jrtoe%) * d(jrtoe%))
cr = 1 / x1
x3 = SQR((kf / kb(jltoe% + 1)) * z(jltoe%) * d(jltoe%))
cl = 1 / x3
x2 = xx(jltoe%) - xx(jrtoe%)
s = x1 + x2
h = yywater(jrtoe%) - yywater(jltoe%)
m = h / (s + x3)
h0 = (h * x3) / (s + x3)
h0r = (h * x1) / (s + x3)
```

```
piezel(1) = ywater(1)
oldpzel(1) = ywater(1)
FOR j% = 2 TO nnodes% - 1
IF well% = 1 AND j% = jwell% THEN
   piezel(j%) = ywell
ELSEIF xx(j%) <= xx(jrtoe%) THEN
   xr = xx(jrtoe%) - xx(j%)
   piezel(j%) = yywater(jrtoe%) - h0r * EXP(-1 * cr * xr)
ELSEIF xx(j%) >= xx(jltoe%) THEN
   xl = xx(j%) - xx(jltoe%)
   piezel(j%) = yywater(jltoe%) + h0 * EXP(-1 * cl * xl)
ELSE
   piezel(j%) = yywater(jrtoe%) - h0r - m * (xx(j%) - xx(jrtoe%))
   kb(j%) = 0
END IF
   oldpzel(j%) = piezel(j%)
NEXT j%
piezel(nnodes%) = ywater(nsecs%)
oldpzel(nnodes%) = ywater(nsecs%)

   ' --- calculate node constants ---

   FOR j% = 2 TO (nnodes% - 1)
      c1(j%) = kf * (d(j%) + d(j% - 1)) * .5 / (xx(j%) - xx(j% - 1))
      c2(j%) = kf * (d(j% + 1) + d(j%)) * .5 / (xx(j% + 1) - xx(j%))
      IF j% = 2 THEN
        c3(j%) = kb(j%) * (((xx(3) - xx(2)) * .5) + (xx(2) - xx(1))) / z(2)
      ELSEIF j% = nnodes% - 1 THEN
        c3(j%) = kb(j%) * (((xx(j% + 1) - xx(j%)) + (xx(j%) - xx(j% - 1)) * .5)) / z(j%)
      ELSEIF j% = jrtoe% THEN
        c3(j%) = kb(j%) * (xx(j%) - xx(j% - 1)) * .5 / z(j%)
      ELSEIF j% = jltoe% THEN
        c3(j%) = kb(j%) * (xx(j% + 1) - xx(j%)) * .5 / z(j%)
      ELSE
        c3(j%) = kb(j%) * (xx(j% + 1) - xx(j% - 1)) * .5 / z(j%)
      END IF
   NEXT j%


   '*** *** SOLVE *** ***
   iter% = 0
   LOCATE 20, 1
   PRINT "Solving         "

   solve:
   iexitmax = 0
   maxres = 0

   '--- iterate forward --
   iter% = iter% + 1
```

```
FOR j% = 2 TO nnodes% - 1
   piezel(j%) = (piezel(j% - 1)) * c1(j%) + (piezel(j% + 1)) * c2(j%) + (yywater(j%)) * c3(j%)
   piezel(j%) = piezel(j%) / (c1(j%) + c2(j%) + c3(j%))
   piezel(j%) = piezel(j%) + .2 * (piezel(j%) - oldpzel(j%)): REM overshoot
   IF well% = 1 AND j% = jwell% THEN
      piezel(j%) = ywell
   END IF
NEXT j%

'--- iterate backward ---
iter% = iter% + 1
FOR j% = nnodes% - 1 TO 2 STEP -1
   piezel(j%) = (piezel(j% - 1)) * c1(j%) + (piezel(j% + 1)) * c2(j%) + (yywater(j%)) * c3(j%)
   piezel(j%) = piezel(j%) / (c1(j%) + c2(j%) + c3(j%))
   IF well% = 1 AND j% = jwell% THEN
      piezel(j%) = ywell
   END IF
   iexit(j%) = (piezel(j%) - yywater(j%)) / (z(j%))
   IF iexit(j%) > iexitmax THEN
      iexitmax = iexit(j%)
      xiexitmax = xx(j%)
   END IF
   res = ABS(piezel(j%) - oldpzel(j%))
   IF res > maxres THEN
           maxres = res
           xmaxres = xx(j%)
        END IF
     NEXT j%

     '--- set old piez els to new ones
     FOR j% = 2 TO nnodes% - 1
        oldpzel(j%) = piezel(j%)
     NEXT j%

     ' --- print iteration and max gradient ---
     IF iter% / 10 = FIX(iter% / 10) THEN
        LOCATE 21, 1
        PRINT USING FormStr1$; iter%, iexitmax, xiexitmax
     END IF

     IF iter% >= maxiters% THEN
        GOTO stopiter
     ELSEIF maxres > tol THEN
        GOTO solve
     END IF
     stopiter:
```

```
' --- calculate residual heads - -
maxreshead = 0
FOR j% = 1 TO nnodes%
   reshead(j%) = piezel(j%) - yywater(j%)
   IF reshead(j%) > maxreshead THEN
      maxreshead = reshead(j%)
      xmaxreshead = xx(j%)
   END IF
NEXT j%

'--- calculate well flow ---
IF well% = 1 THEN
   j% = jwell%
   Qin = kf * ((piezel(j% - 1) - piezel(j%)) / (xx(j%) - xx(j% - 1))) * (d(j%) + d(j% - 1)) / 2
   Qout = kf * ((piezel(j%) - piezel(j% + 1)) / (xx(j% + 1) - xx(j%))) * (d(j% + 1) + d(j%)) / 2
   Qup = kb(j%) * ((piezel(j%) - yywater(j%)) / z(j%)) * (xx(j% + 1) - xx(j% - 1)) / 2
   Qwell = Qin - Qout - Qup
   Qwgal = Qwell * 7.48
END IF

'*** WRITE FINAL HEADS AND GRADIENTS TO FILE ****
PRINT #2,
PRINT #2, "      xx  piezel reshead       z       i"
PRINT #2,
FOR j% = 1 TO nnodes%
PRINT #2, USING FormStr4$; xx(j%); piezel(j%); reshead(j%); z(j%); iexit(j%)
NEXT j%
IF well% = 1 THEN
   PRINT #2,
   PRINT #2, USING "Well flow = ###.### ft^3/min/ft"; Qwell
   PRINT #2, USING "Well flow = ###.### gpm/ft"; Qwgal

  END IF

  CLOSE 2

  ' *** DISPLAY FINAL RESULTS ***
  LOCATE 20, 1
  PRINT "SOLUTION COMPLETE    "
  LOCATE 20, 50
  PRINT "OUTPUT FILE: "; outfile$
  LOCATE 21, 1
  PRINT USING FormStr1$; iter%, iexitmax, xiexitmax
  LOCATE 22, 1
  PRINT USING FormStr2$; maxreshead, xmaxreshead
  IF well% = 1 THEN
     LOCATE 21, 48
     PRINT USING "Well flow = ###.### gpm/ft"; Qwgal
  END IF

  GOSUB graphpiez
```

```
' --- check for new window ---
checkwindow:
LOCATE 23, 1
PRINT blank40$; blank40$;
LOCATE 24, 1
PRINT blank40$; blank40$;
LOCATE 23, 1
INPUT ; "Change graphics window (Y or N) "; code$
IF code$ = "Y" OR code$ = "y" THEN
   LOCATE 23, 1
   PRINT "Current xwmin, xwmax, ywmin, ywmax:";
   LOCATE 23, 40
   PRINT USING " ##### ##### ##### #####"; xwmin, xwmax, ywmin, ywmax;
   LOCATE 24, 1
   PRINT "Enter new values with commas: ";
   LOCATE 24, 40
   INPUT ; xwmin, xwmax, ywmin, ywmax
   CLS
   WINDOW (xwmin, ywmin)-(xwmax, ywmax)
   GOSUB drawsection
   GOSUB graphnodes
   GOSUB graphpiez
   GOSUB displaytitles
   GOTO checkwindow
END IF

'--- print output file to printer if desired ---
printer:
LOCATE 23, 1
INPUT ; "Dump output to printer (Y or N) "; code$
IF code$ = "Y" OR code$ = "y" THEN
   GOTO printer2
ELSEIF code$ = "N" OR code$ = "n" THEN
   GOTO recycle

   ELSE GOTO printer
   END IF

   printer2:
   LPRINT "PROGRAM LEVEEMSU "; changedate$; " edition"
   LPRINT DATE$
   LPRINT TIME$
   LPRINT "INPUT FILE: "; infile$
   LPRINT "OUTPUT FILE: "; outfile$
   LPRINT
   LPRINT title1$
   LPRINT title2$
   LPRINT
   LPRINT "KF = "; kf
   LPRINT "PERMFLAGR = "; permflagr$; "    PERMRIV  = "; permriv
   LPRINT "PERMFLAGL = "; permflagl$; "    PERMLAND = "; permland
```

```
IF well% = 1 THEN
   LPRINT
   LPRINT "WELL LINE AT X   = "; xwell
   LPRINT "AVGERAGE PIEZ EL = "; ywell
END IF
LPRINT
LPRINT "      xx      yy1      yy2      yy3 yywater      d      z          kb"
LPRINT
FOR j% = 1 TO nnodes%
LPRINT USING FormStr3$; xx(j%); yy1(j%); yy2(j%); yy3(j%); yywater(j%); d(j%); z(j%); kb(j%)
NEXT j%
LPRINT
LPRINT "      xx  piezel reshead       z       i"
LPRINT
FOR j% = 1 TO nnodes%
LPRINT USING FormStr4$; xx(j%); piezel(j%); reshead(j%); z(j%); iexit(j%)
NEXT j%
IF well% = 1 THEN
   LPRINT
   LPRINT USING "Well flow = ###.### ft^3/min/ft"; Qwell
   LPRINT USING "Well flow = ###.### gpm/ft"; Qwgal
END IF

' --- check for new problem ---
recycle:
LOCATE 24, 1
INPUT ; "Run again (Y or N) "; code$
IF code$ = "Y" OR code$ = "y" THEN
   GOTO start
ELSEIF code$ = "N" OR code$ = "n" THEN
   GOTO terminate
ELSE GOTO recycle
END IF

terminate:
END

' ------SUBROUTINES-------

   infileerror:
   PRINT "error in input file"

   errorhandler:
   PRINT "fatal error"
```

```
' --- MSU Flag---
msuflag:
COLOR 15, 2
FOR i% = 1 TO 7
  LOCATE i%, 50
  PRINT "                "
NEXT i%
x$ = CHR$(219)
LOCATE 2, 55
PRINT x$; x$; x$; x$; x$
LOCATE 3, 55
PRINT x$
LOCATE 4, 55
PRINT x$; x$; x$; x$; x$;
LOCATE 5, 59
PRINT x$;
LOCATE 6, 55
PRINT x$; x$; x$; x$; x$;
RETURN

' -- CORPS FLAG ---
corpsflag:
s$ = CHR$(32)
COLOR 15, 4
LOCATE 9, 50
PRINT s$; s$; s$; s$; s$; s$; s$; s$; s$; s$; s$; s$; s$; s$; s$;
LOCATE 10, 50
PRINT s$; s$; s$; s$; s$; s$; s$; s$; s$; s$; s$; s$; s$; s$; s$;
LOCATE 11, 50
PRINT s$; s$; s$; x$; x$; s$; x$; x$; x$; s$; x$; x$; s$; s$; s$;
LOCATE 12, 50
PRINT s$; s$; s$; s$; x$; x$; x$; x$; x$; x$; x$; s$; s$; s$; s$;
LOCATE 13, 50
PRINT s$; s$; s$; x$; x$; x$; x$; s$; x$; x$; x$; x$; s$; s$; s$;
LOCATE 14, 50
PRINT s$; s$; s$; s$; s$; s$; s$; s$; s$; s$; s$; s$; s$; s$; s$;
LOCATE 15, 50
PRINT s$; s$; s$; s$; s$; s$; s$; s$; s$; s$; s$; s$; s$; s$; s$;
RETURN

' *** Plot Levee Section ***
drawsection:
' --- outline pervious substratum ---
LINE (x(1), y1(1))-(x(1), y2(1)), sandcolor
LINE (x(nsecs%), y1(nsecs%))-(x(nsecs%), y2(nsecs%)), sandcolor
FOR j% = 1 TO nsecs% - 1
```

```
   LINE (x(j%), y1(j%))-(x(j% + 1), y1(j% + 1)), sandcolor
   LINE (x(j%), y2(j%))-(x(j% + 1), y2(j% + 1)), sandcolor
NEXT j%
'--- paint pervious substratum ---
ya = (y2(nrivsecs% + 1) + ywmin) / 2
yb = (y2(nrivsecs% + 1) + y1(nrivsecs% + 1)) / 2
IF ya > yb THEN
   y = ya
ELSE
   y = yb
END IF
IF chip$ = "egac" THEN
   PAINT (x(nrivsecs% + 1), y), sandcolor
ELSEIF chip$ = "egam" THEN
   PAINT (x(nrivsecs% + 1), y), sandtile$, 7
ELSE
   PAINT (x(nrivsecs% + 1), y), sandtile$
END IF
' --- outline impervious topstratum ---
LINE (x(1), y2(1))-(x(1), y3(1)), claycolor
LINE (x(nsecs%), y2(nsecs%))-(x(nsecs%), y3(nsecs%)), claycolor
FOR j% = 1 TO nsecs% - 1
   LINE (x(j%), y2(j%))-(x(j% + 1), y2(j% + 1)), claycolor
   LINE (x(j%), y3(j%))-(x(j% + 1), y3(j% + 1)), claycolor
NEXT j%
' --- paint topstratum ---
IF chip$ = "egac" THEN
   FOR j% = 2 TO nsecs% - 1
      y = (y2(j%) + y3(j%)) / 2
      PAINT (x(j%), y), claycolor
   NEXT j%
END IF
' --- levee---
xrtoe = x(nrivsecs%)
xltoe = x(nrivsecs% + 1)
xlevmid = (xrtoe + xltoe) / 2
yrtoe = y3(nrivsecs%)
yltoe = y3(nrivsecs% + 1)
ylevmid = (y3(nrivsecs%) + y3(nrivsecs% + 1)) / 2
LINE (xrtoe, yrtoe)-(xlevmid, yriv), leveecolor
LINE (xlevmid, yriv)-(xltoe, yltoe), leveecolor
LINE (xrtoe, yrtoe)-(xltoe, yltoe), leveecolor
PAINT (xlevmid, (ylevmid + yriv) / 2), leveecolor
' --- water ---
LINE (x(1), yriv)-(xrtoe, yriv), watercolor
FOR i% = nrivsecs% + 1 TO nsecs% - 1
   LINE (x(i%), ywater(i%))-(x(i% + 1), ywater(i% + 1)), watercolor
NEXT i%
```

```
LOCATE 1, 39
PRINT ywmax;
LOCATE 19, 39
PRINT ywmin;
LOCATE 12, 1
PRINT xwmin;

LOCATE 12, 74
PRINT xwmax;

RETURN

' --- display titles ---
displaytitles:
LOCATE 1, 1
PRINT "INPUT FILE: "; infile$
LOCATE 2, 1
PRINT title1$
LOCATE 3, 1
PRINT title2$
LOCATE 1, 65
PRINT DATE$
LOCATE 2, 65
PRINT TIME$
RETURN

'--- graph nodes ---
graphnodes:
radius = .005 * (xwmax - xwmin)
aspect = .7
FOR j% = 1 TO nnodes%
  CIRCLE (xx(j%), yy2(j%)), radius, , , , aspect
NEXT j%
RETURN

'--- graph piezometric line ---
graphpiez:
FOR j% = 1 TO nnodes% - 1
   LINE (xx(j%), piezel(j%))-(xx(j% + 1), piezel(j% + 1))
NEXT j%
RETURN

END
```

APPENDIX G: NOTATION

d	Thickness of pervious substratum
h_o	Residual head at levee toe
h_x	Residual head at distance x from landside toe levee
H	Net head on levee
k_b	Permeability of top blanket
k_{bl}	Permeability of landside top blanket
k_{br}	Permeability of riverside top blanket
k_f	Permeability of pervious substratum
L_1	Distance from open seepage entrance to riverside levee toe
L_2	Distance from riverside levee toe to landside levee toe
L_3	Distance from landside levee toe to open exit
Q	Flow
x_3	Distance from landside levee toe to effective seepage exit
z	Thickness of top blanket
MSL	Mean Sea Level
MGL	Mean Gulf Level
NGVD	National Geodetic Vertical Datum